CLOUD TOP PARAMETERS

VISIBLE/INFRARED IMAGER/RADIOMETER SUITE ALGORITHM THEORETICAL BASIS DOCUMENT

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

GLOSSARY OF ACRONYMS

ARM	Atmospheric Radiation Measurement program
ATBD	Algorithm Theoretical Basis Document
AVHRR	Advanced Very High Resolution Radiometer
CDR	Crtical Design Review
CLW	Cloud Liquid Water
CMIS	Conical Scanning Microwave Imager/Sounder
COT	Cloud Optical Thickness
CrIS	Cross-track Infrared Sounder
CMIS	Conical Scanning Microwave Imager/Sounder
CSSM	Cloud Scene Simulation Model
CTH	Cloud Top Height
CTP	Cloud Top Pressure
CTT	Cloud Top Temperature
DISORT	Discrete Ordinate Radiative Transfer
DoD	Department of Defense
EDR	Environmental Data Record
EOS	Earth Observing System
EPS	Effective Particle Size
FIRE	First ISCCP Regional Experiment
GSD	Ground Sampling Distance
HC	Horizontal Cell
HCS	Horizontal Cell Size
HIS	Horizontal Sampling Interval
IPO	Integrated Program Office
IPT	Integrated Product Team
IR	Infrared
ISCCP	International Satellite Cloud Climatology Program
IWC	Ice Water Content
LOS	Line-of-Sight
LUT	Look-Up Table
MAS	MODIS Airborne Simulator
MODIS	Moderate Resolution Imaging Spectroradiometer

MODTRAN	Moderate Resolution Atmospheric Radiance and Transmittance Model
MTF	Modulation Transfer Function
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
OLS	Operational Linescan System
RSS	Root of the Sum of the Squares
SBRS	Santa Barbara Remote Sensing
SNR	Sensor Signal-to-Noise Ratio
SRD	Sensor Requirements Document
TBD	To be Determined
TBR	To be Reviewed
TIROS	Television Infrared Observation Satellite
TOA	Top of the Atmosphere
UCLA	University of California at Los Angles
VIIRS	Visible/Infrared Imager/Radiometer Suite

DEFINITION OF SYMBOLS

z_{cb} (km - kilometers)	Cloud Base Height
r_e (µm or um (in figures) – micrometers)	Cloud Mean Effective Particle Radius
D_e (µm - micrometers)	Cloud Mean Effective Particle Size (diameter)
τ (unitless)	Cloud Optical Depth
z (km - kilometers)	Height
z_{cb} (km - kilometers)	Cloud Base Height
z_{ct} (km - kilometers)	Cloud Top Height
p (mb - millibars)	Pressure
p_{ct} (mb - millibars)	Cloud Top Pressure
T_{cb}(K - degrees Kelvin)	Cloud Base Temperature
T_{ct}(K - degrees Kelvin)	Cloud Top Temperature
μ_0	Cosine of Solar Zenith Angle
μ	Cosine of Sensor Zenith Angle
I	Radiance
$\Delta\phi$ (angular degrees)	Sun-Sensor Relative Azimuth Angle
ϕ (angular degrees)	Sensor Azimuth Angle
θ (angular degrees)	Sensor Zenith Angle
ϕ_0 (angular degrees)	Solar Azimuth Angle
θ_0 (angular degrees)	Solar Zenith Angle
λ	Wavelength

ABSTRACT

The Visible/Infrared Imager/Radiometer Suite (VIIRS) Cloud Top Parameters Algorithm estimates cloud top temperature, pressure, and height using VIIRS radiances, other VIIRS Cloud Environmental Data Records (EDRs), derived quantities (e.g., cloud mask and phase), and scenario parameters (sun/sensor geometry, atmospheric scenario, etc.). Three retrieval algorithms are used to determine cloud top parameters: The Window Infrared (IR) Algorithm is used during daytime to compute cloud top height using radiance measurements in the 10.8 µm band and radiative transfer analysis with the scenario parameters. It may be applicable at night as well for optically thick water clouds (which is typically the case). The window IR algorithm has a heritage from the International Satellite Cloud Climatology Program (ISCCP), which uses the 10.8 µm channel to derive cloud top temperature under opaque cloudy conditions. The adjusted cloud top pressure that corresponds to cloud top temperature is found from the temperature profile (Rossow, et al., 1991). The algorithm derives cloud top height (z_{ct}) and an Interpolation Algorithm uses z_{ct} together with sounding data to determine cloud top temperature (T_{ct}) and cloud top pressure (p_{ct}). The UCLA IR Cirrus and water cloud Parameter Retrieval Algorithms (Ou *et al.*, 2001) compute T_{ct} as well as cloud effective particle size and optical depth for cirrus and water clouds, respectively, both day and night. The Interpolation Algorithm uses T_{ct} as determined by the UCLA algorithm, together with sounding data, to determine z_{ct} and p_{ct}.

The Window IR Algorithm and the Cloud Top Parameter Interpolation Algorithm are described in detail in this report. Comments are also made concerning potential alternative or complementary algorithms to retrieve cloud top parameters. In addition, this report provides a description of data flow, the retrieval algorithms and their physical basis, flowdown and sensitivity studies, and algorithm implementation considerations. Measurement requirements for cloud top parameters are specified in the VIIRS Sensor Requirements Document (SRD) and are repeated in this report. Window IR algorithm cloud top parameters retrieval performance analysis has been conducted. Based on current simulation results, that procedure is projected to meet the threshold requirement. Further improvement and validation of algorithms will be conducted after critical design review.

1.0 INTRODUCTION

1.1 PURPOSE

This document describes algorithms that will be used to retrieve cloud top parameters using data from the prospective Visible/Infrared Imager/Radiometer Suite (VIIRS) instrument. A description is provided of data flow, the retrieval algorithms and their physical basis, flowdown, EDR performance and sensitivity studies, and implementation considerations. Measurement requirements for cloud top parameters, including cloud top temperature, pressure, and height, are identified in the VIIRS Sensor Requirements Document (SRD).

1.2 SCOPE

This document focuses on the theoretical basis for retrieval of cloud top temperature, pressure, and height using VIIRS data. Because multiple algorithms are used for cloud parameter retrieval (i.e., retrieval of cloud optical depth, effective particle size, base height, and amount/layers) and because these parameters are related to the cloud top parameters, frequent reference is made to the other cloud parameter Algorithm Theoretical Basis Documents (ATBDs). In addition, some algorithms estimate multiple parameters, including cloud top temperature. The details of these algorithms are not repeated here; instead, the appropriate ATBD is referenced.

The document is organized into five major sections. The first section is an introduction. The next section provides an overview of the retrieval algorithms, including objectives, instrument characteristics, and retrieval strategy. Section 3 describes the retrieval algorithms and their physical basis, data requirements and issues, algorithm sensitivities to input and flowdown, error budget, practical considerations, validation, and a development schedule. Section 4 provides a brief description of major algorithm assumptions and limitations, and Section 5 is a list of references cited.

1.3 VIIRS DOCUMENTS

VIIRS Sensor Requirements Document (SRD) for National Polar-orbiting Operational Environmental Satellite System (NPOESS) Spacecraft and Sensors. Associate Directorate for Acquisition NPOESS Integrated Program Office (IPO). Version 2, Revision a, 4 November 1999. F04701-97-C-0028.

VIIRS System Specification Document. SS154640.

VIIRS Cloud Effective Particle Size and Cloud Optical Thickness ATBD, Version 5, March 2002. Y2393.

VIIRS Cloud Cover/Layers ATBD, Version 5, March 2002. Y3292.

VIIRS Error Budget. Y3249.

1.4 REVISION

This is the fifth revision of this document, dated March 2002.

2.0 EXPERIMENT OVERVIEW

This section contains three major subsections. Subsection 2.1 describes the objectives of the cloud top parameter retrievals. Subsection 2.2 describes the characteristics of the VIIRS instrument. Subsection 2.3 addresses the cloud top parameter retrieval strategy.

2.1 OBJECTIVES OF CLOUD TOP PARAMETER RETRIEVALS

The cloud top parameter retrieval algorithms, together with the prospective VIIRS sensor, have been developed to meet SRD requirements for cloud top temperature, pressure, and height. For reference, these requirements are provided in Sections 2.1.1 through 2.1.3. Under the VIIRS sensor/algorithm development concept, these requirements were "flowed down" to the design of the most cost-effective sensor/algorithm solution that meets the SRD requirements. This was accomplished through a series of flowdown tests and error budget analyses, which effectively simulated sensor and algorithm performance over a range of environmental and operational scenarios. The error budgets are briefly described in Section 3.3 and described in much more detail in the Raytheon VIIRS Error Budget (Y3249).

2.1.1 Cloud Top Height

The System Specification Document provides the following definition for Cloud Top Height:

> *"Cloud Top Height(CTH) is defined for each cloud-covered Earth location as the set of heights of the tops of the cloud layers overlying the location. The reported heights are horizontal spatial averages over a cell, i.e., a square region of the Earth's surface. If a cloud layer does not extend over an entire cell, the spatial average is limited to the portion of the cell that is covered by the layer. CTH is not defined or reported for cells that are clear. As a threshold, only the height at the top of the highest altitude cloud layer is required. The objective is to report the CTH for all distinct cloud layers. This EDR must be generated as a dual product at two spatial scales, one meeting the moderate HCS requirements and the other meeting the fine HCS requirements. The moderate HCS product is the operational requirement, and the fine HCS product is for augmented applications only."*

Table 1 summarizes the System Specification requirements for this parameter.

Table 1. System Specification Requirements for Cloud Top Height

Requirement Number	Parameter	Requirement
SSV0251	EDR CLTPHT Moderate HCS worst case:	25 km
SSV0252	EDR CLTPHT Fine HCS at nadir:	5 km
SSV0253	EDR CLTPHT HRI:	HCS
SSV0254	EDR CLTPHT Horizontal Coverage:	Global
SSV0255	EDR CLTPHT Vertical Reporting Interval:	Up to 4 layers
SSV0256	EDR CLTPHT Measurement Range:	0 to 20 km
SSV0257	EDR CLTPHT Moderate Measurement Accuracy, Cloud layer optical thickness > 1.0 day water cloud:	0.5 km
SSV0806	EDR CLTPHT Moderate Measurement Accuracy, Cloud layer optical thickness > 1.0 night water cloud:	1.0 km
SSV0807	EDR CLTPHT Moderate Measurement Accuracy, Cloud layer optical thickness > 1.0 ice cloud (day and night):	1.0 km
SSV0258	EDR CLTPHT Moderate Measurement Accuracy, Cloud layer optical thickness ≤ 1.0:	2.0 km
SSV0259	EDR CLTPHT Moderate Measurement Precision:	0.3 km
SSV0261	EDR CLTPHT Fine Measurement Uncertainty, Cloud layer optical thickness > 1.0, day water cloud:	0.5 km
SSV0899	EDR CLTPHT Fine Measurement Uncertainty, Cloud layer optical thickness > 1.0, night water cloud:	1.0 km
SSV0900	EDR CLTPHT Fine Measurement Uncertainty, Cloud layer optical thickness <= 1.0, day water cloud:	2.0 km
SSV0901	EDR CLTPHT Fine Measurement Uncertainty, Cloud layer optical thickness <= 1.0, night water cloud:	2.0 km
SSV0262	EDR CLTPHT Fine Measurement Uncertainty, ice cloud (day and night):	1 km
SSV0263	EDR CLTPHT Measurement Long Term Stability:	0.2 km
SSV0265	EDR CLTPHT Swath Width:	3000 km

*Applies at nadir for fine resolution product.

2.1.2 Cloud Top Pressure

The System Specification provides the following definition for Cloud Top Pressure:

"Cloud Top Pressure (CTP) is defined for each cloud-covered Earth location as the set of atmospheric pressures at the tops of the cloud layers overlying the location. The reported pressures are horizontal spatial averages over a cell, i.e., a square region of the Earth's surface. If a cloud layer does not extend over an entire cell, the spatial average is limited to the portion of the cell that is covered by the layer. CTP is not defined or reported for cells that are clear. As a threshold, only the pressure at the top of the highest altitude cloud layer is required. The objective is to report the CTP for all distinct cloud layers. This EDR must be generated as a dual product at two spatial scales, one meeting the moderate HCS requirements and the other meeting the fine HCS requirements. The moderate HCS product is the operational requirement, and the fine

HCS product is for augmented applications only."

Table 2 summarizes the System Specification Document requirements for this parameter.

Table 2. System Specification Requirements for Cloud Top Pressure

Requirement Number	Parameter	Requirement
SSV0267	EDR CLTPPR Moderate HCS worst case:	12.5 km
SSV0268	EDR CLTPPR Fine HCS at nadir:	5 km
SSV0269	EDR CLTPPR HRI:	HCS
SSV0270	EDR CLTPPR Horizontal Coverage:	Global
SSV0271	EDR CLTPPR Measurement Range:	50 to 1050 mb
SSV0272	EDR CLTPPR Moderate Measurement Accuracy, 0 to 3 km altitude, optical thickness <= 1.0, day water cloud:	100 mb
SSV0902	EDR CLTPPR Moderate Measurement Accuracy, 0 to 3 km altitude, optical thickness <= 1.0, night water cloud:	100 mb
SSV0903	EDR CLTPPR Moderate Measurement Accuracy, 0 to 3 km altitude, optical thickness > 1.0, day water cloud:	40 mb
SSV0904	EDR CLTPPR Moderate Measurement Accuracy, 0 to 3 km altitude, optical thickness > 1.0, night water cloud:	70 mb
SSV0273	EDR CLTPPR Moderate Measurement Accuracy, 3 to 7 km altitude, optical thickness <= 1.0:	65 mb
SSV0905	EDR CLTPPR Moderate Measurement Accuracy, 3 to 7 km altitude altitude, optical thickness > 1.0:	40 mb
SSV0274	EDR CLTPPR Moderate Measurement Accuracy, > 7 km altitude:	30 mb
SSV0275	EDR CLTPPR Moderate Measurement Precision, 0 to 3 km altitude:	25 mb
SSV0276	EDR CLTPPR Moderate Measurement Precision, 3 to 7 km altitude:	20 mb
SSV0277	EDR CLTPPR Moderate Measurement Precision, > 7 km altitude:	13 mb
SSV0278	EDR CLTPPR Fine Measurement Uncertainty, 0 to 3 km altitude, optical thickness <= 1.0, day water cloud:	130 mb
SSV0906	EDR CLTPPR Fine Measurement Uncertainty, 0 to 3 km altitude, optical thickness <= 1.0, night water cloud:	100 mb
SSV0907	EDR CLTPPR Fine Measurement Uncertainty, 0 to 3 km altitude, optical thickness > 1.0, day water cloud:	40 mb
SSV0908	EDR CLTPPR Fine Measurement Uncertainty, 0 to 3 km altitude, optical thickness > 1.0, night water cloud:	80 mb
SSV0810	EDR CLTPPR Fine Measurement Uncertainty, 3 to 7 km altitude, optical thickness <= 1.0:	70 mb
SSV0909	EDR CLTPPR Fine Measurement Uncertainty, 3 to 7 km altitude, optical thickness > 1.0:	45 mb
SSV0811	EDR CLTPPR Fine Measurement Uncertainty, > 7 km altitude:	30 mb
SSV0279	EDR CLTPPR Measurement Long Term Stability, 3 km altitude:	10 mb
SSV0280	EDR CLTPPR Measurement Long Term Stability, 3 to 7 km altitude:	7 mb
SSV0281	EDR CLTPPR Measurement Long Term Stability, > 7 km altitude:	5 mb
SSV0283	EDR CLTPPR Swath Width:	3000 km

*Applies at nadir for fine resolution product.

2.1.3 Cloud Top Temperature

The System Specification Document provides the following definition for Cloud Top Temperature:

> *"Cloud Top Temperature (CTT) is defined for each cloud-covered Earth location as the set of atmospheric temperatures at the tops of the cloud layers overlying the location. The reported temperatures are horizontal spatial averages over a cell, i.e., a square region of the Earth's surface. If a cloud layer does not extend over an entire cell, the spatial average is limited to the portion of the cell that is covered by the layer. CTT is not defined or reported for cells that are clear. As a threshold, only the temperature at the top of the highest altitude cloud layer is required. The objective is to report the CTT for all distinct cloud layers. This EDR must be generated as a dual product at two spatial scales, one meeting the moderate HCS requirements and the other meeting the fine HCS requirements. The moderate HCS product is the operational requirement, and the fine HCS product is for augmented applications only."*

Table 3 summarizes the System Specification requirements for this parameter.

Table 3. System Specification Requirements for Cloud Top Temperature

Requirement Number	Parameter	Requirement
SSV0285	EDR CLTPTM Moderate HCS worst case:	25 km
SSV0286	EDR CLTPTM Fine HCS at nadir:	5 km
SSV0287	EDR CLTPTM HRI:	HCS
SSV0288	EDR CLTPTM Horizontal Coverage:	Global
SSV0289	EDR CLTPTM Measurement Range:	175 K to 310 K
SSV0290	EDR CLTPTM Moderate Measurement Accuracy, Cloud layer optical thickness > 1.0, water cloud day:	2 K
SSV0812	EDR CLTPTM Moderate Measurement Accuracy, Cloud layer optical thickness > 1.0, water cloud night:	3 K
SSV0813	EDR CLTPTM Moderate Measurement Accuracy, Cloud layer optical thickness > 1.0, ice cloud (day and night):	3 K
SSV0291	EDR CLTPTM Moderate Measurement Accuracy, Cloud layer optical thickness ≤ 1.0	6 K
SSV0292	EDR CLTPTM Moderate Measurement Precision	1.5 K
SSV0295	EDR CLTPTM Fine Measurement Uncertainty, water cloud:	3 K
SSV0816	EDR CLTPTM Fine Measurement Uncertainty, ice cloud:	5 K
SSV0893	EDR CLTPTM Long-term Stability	1 K
SSV0298	EDR CLTPTM Swath Width	3000 km

*Applies at nadir for fine resolution product.

2.2 INSTRUMENT CHARACTERISTICS

The VIIRS instrument will now be briefly described to clarify the context of the descriptions of the Cloud Top parameter EDR presented in this document. VIIRS can be pictured as a convergence of three existing sensors, two of which have seen extensive operational use at this writing.

The Operational Linescan System (OLS) is the operational visible/infrared scanner for the Department of Defense (DoD). Its unique strengths are controlled growth in spatial resolution through rotation of the ground instantaneous field of view (GIFOV) and the existence of a low-level light sensor (LLLS) capable of detecting visible radiation at night. OLS has primarily served as a data source for manual analysis of imagery. The Advanced Very High Resolution Radiometer (AVHRR) is the operational visible/infrared sensor flown on the National Oceanic and Atmospheric Administration (NOAA) Television Infrared Observation Satellite (TIROS-N) series of satellites (Planet, 1988). Its unique strengths are low operational and production cost and the presence of five spectral channels that can be used in a wide number of combinations to produce operational and research products. In December 1999, the National Aeronautics and Space Administration (NASA) launched the Earth Observing System (EOS) morning satellite, *Terra*, which includes the Moderate Resolution Imaging Spectroradiometer (MODIS). This sensor possesses an unprecedented array of thirty-two spectral bands at resolutions ranging from 250 m to 1 km at nadir, allowing for unparalleled accuracy in a wide range of satellite-based environmental measurements.

VIIRS will reside on a platform of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) series of satellites. It is intended to be the product of a convergence between DoD, NOAA and NASA in the form of a single visible/infrared sensor capable of satisfying the needs of all three communities, as well as the research community beyond. As such, VIIRS will require three key attributes: high spatial resolution with controlled growth off nadir, minimal production and operational cost, and a large number of spectral bands to satisfy the requirements for generating accurate operational and scientific products.

Figure 1 illustrates the design concept for VIIRS, designed and built by Raytheon Santa Barbara Remote Sensing (SBRS). At its heart is a rotating telescope scanning mechanism that minimizes the effects of solar impingement and scattered light. Calibration is performed onboard using a solar diffuser for short wavelengths and a V-groove blackbody source and deep space view for thermal wavelengths. A solar diffuser stability monitor (SDSM) is also included to track the performance of the solar diffuser. The nominal altitude for NPOESS will be 833 km. The VIIRS scan will extend to 56 degrees on either side of nadir.

The VIIRS SRD places explicit requirements on spatial resolution for the Imagery EDR. Specifically, the horizontal spatial resolution (HSR) of bands used to meet threshold Imagery EDR requirements must be no greater than 400 m at nadir and 800 m at the edge of the scan. This led to the development of a unique scanning approach which optimizes both spatial resolution and signal to noise ratio (SNR) across the scan. The concept is summarized in Figure 2 for the imagery bands; the nested lower resolution radiometric bands follow the same paradigm at exactly twice the size. The VIIRS detectors are rectangular, with the smaller dimension projecting along the scan. At nadir, three detector footprints are aggregated to form a single VIIRS "pixel." Moving along the scan away from nadir, the detector footprints become larger both along track and along scan, due to geometric effects and the curvature of the Earth. The effects are much larger along scan. At around 32 degrees in scan angle, the aggregation scheme is changed from 3x1 to 2x1. A similar switch from 2x1 to 1x1 aggregation occurs at 48 degrees. The VIIRS scan consequently exhibits a pixel growth factor of only 2 both along track and along scan, compared with a growth factor of 6 along scan which would be realized without the use of the aggregation scheme. Figure 3 illustrates the benefits of the aggregation scheme for spatial resolution.

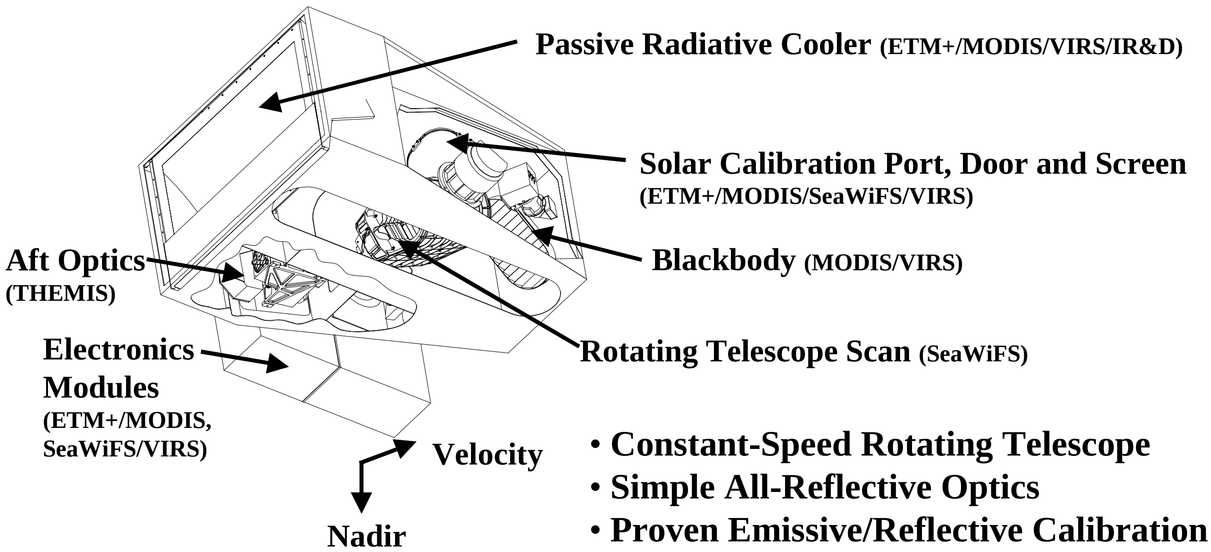


Figure 1. Summary of VIIRS design concepts and heritage.

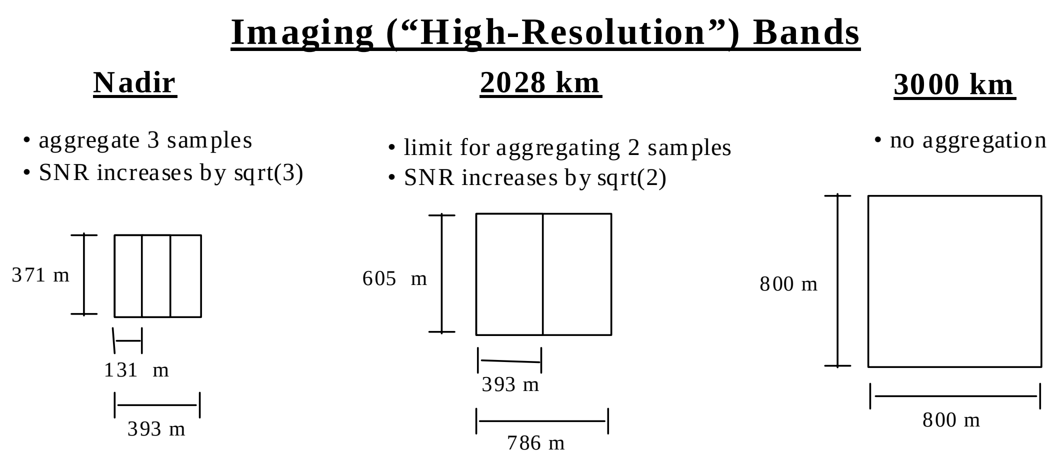


Figure 2. VIIRS detector footprint aggregation scheme for building "pixels." Dimensions are approximate.

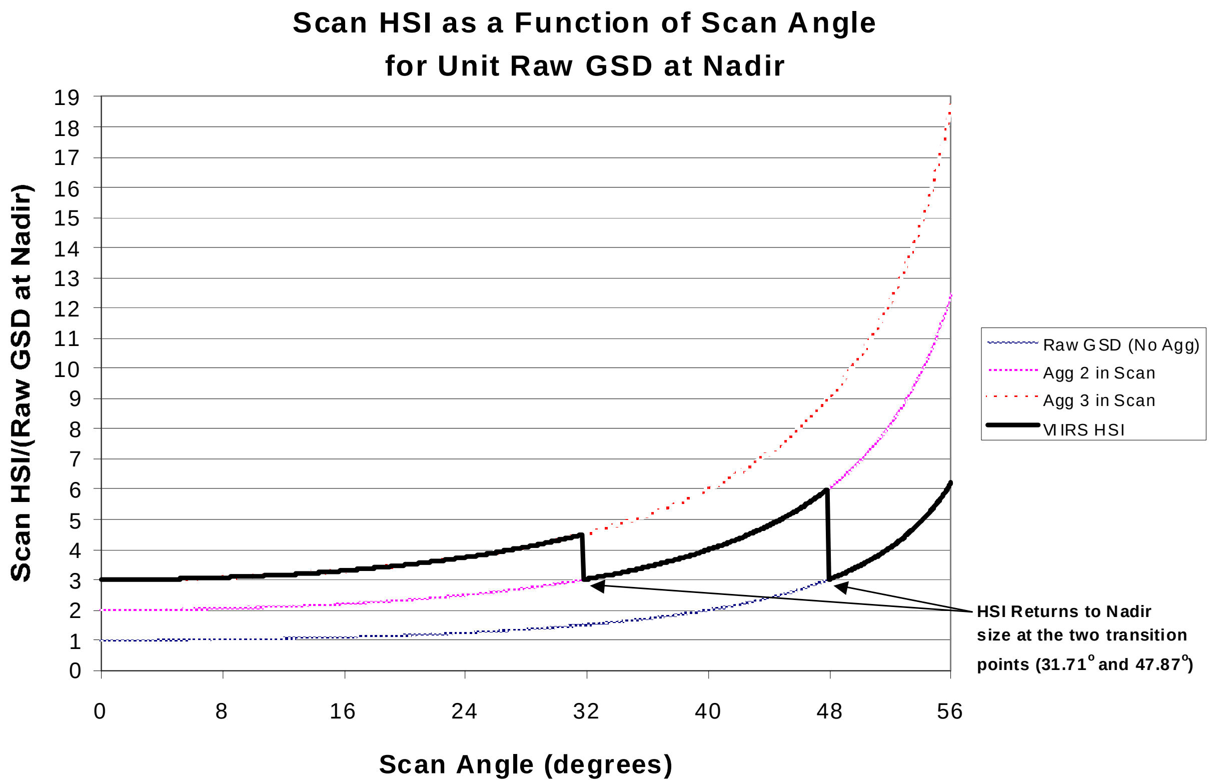


Figure 3. Benefits of VIIRS aggregation scheme in reducing pixel growth at edge of scan.

The VIIRS baseline performance is summarized in Table 4 and Table 5 for low and high radiances, respectively. The high radiance numbers for the middle and long-wave infrared bands are more relevant to Cloud Top Parameters retrievals in general. The exact values of these numbers can be expected to change through the design and fabrication stages for VIIRS; each release of this document will reflect the latest numbers at the time of release. However, minor discrepancies may be noted if the document is being read a significant amount of time since the most recent release. The positioning of the VIIRS spectral bands is summarized in Figure 4 through Figure 7.

Table 4. VIIRS baseline performance and specifications, low radiance range.

Band Name	Wavelength (μm)	Bandwidth (μm)
Day Night Band	0.700	0.4000
M1	0.412	0.0200
M2	0.445	0.0180
M3	0.488	0.0200
M4	0.555	0.0200
I1	0.640	0.0800
M5	0.672	0.0200
M6	0.746	0.0150
I2	0.865	0.0390
M7	0.865	0.0390

Table 5. VIIRS baseline performance and specifications, high radiance range.

Band Name	Wavelength (μm)	Bandwidth (μm)
M8	1.240	0.0200
M9	1.378	0.0150
I3	1.610	0.0600
M10	1.610	0.0600
M11	2.250	0.0500
I4	3.740	0.3800
M12	3.700	0.1800
M13	4.050	0.1550
M14	8.550	0.3000
M15	10.7625	1.0000
I5	11.450	1.9000
M16	12.0125	0.9500

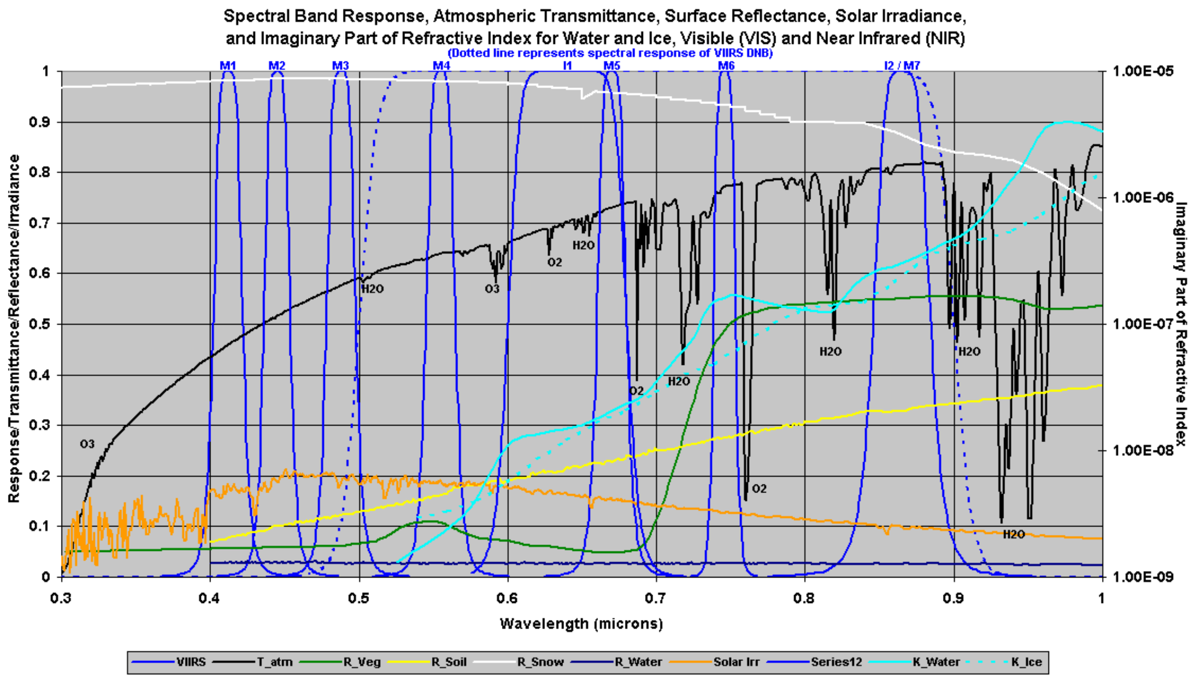


Figure 4. VIIRS spectral bands, visible and near infrared.

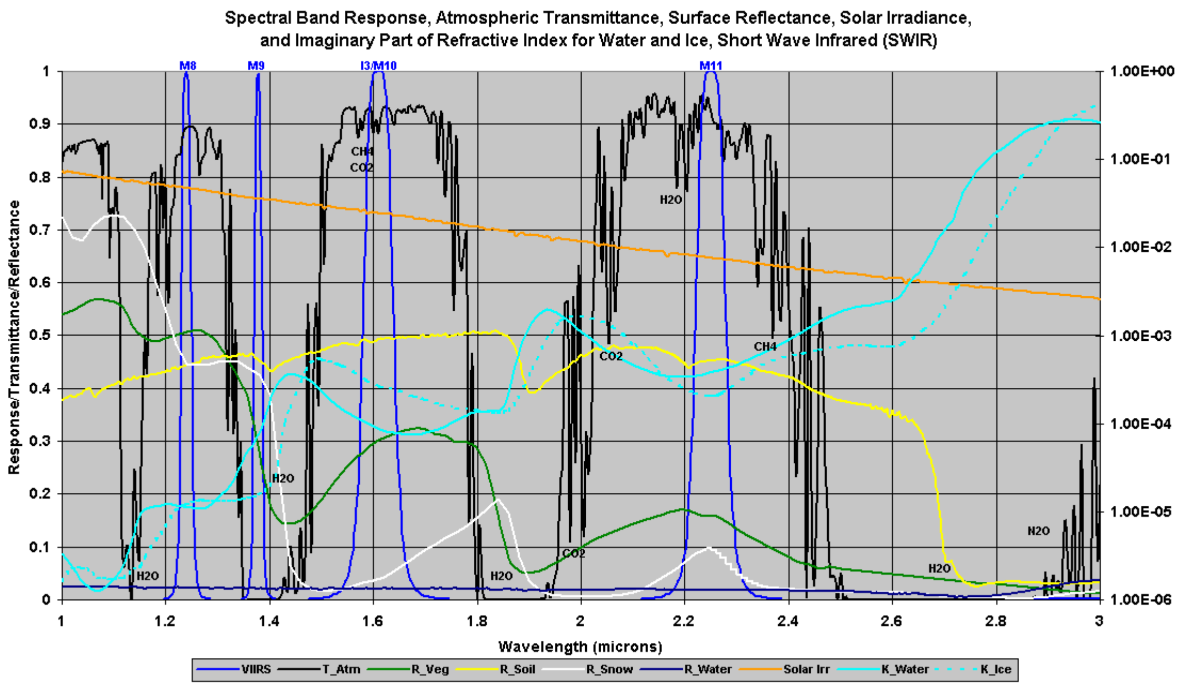


Figure 5. VIIRS spectral bands, short wave infrared.

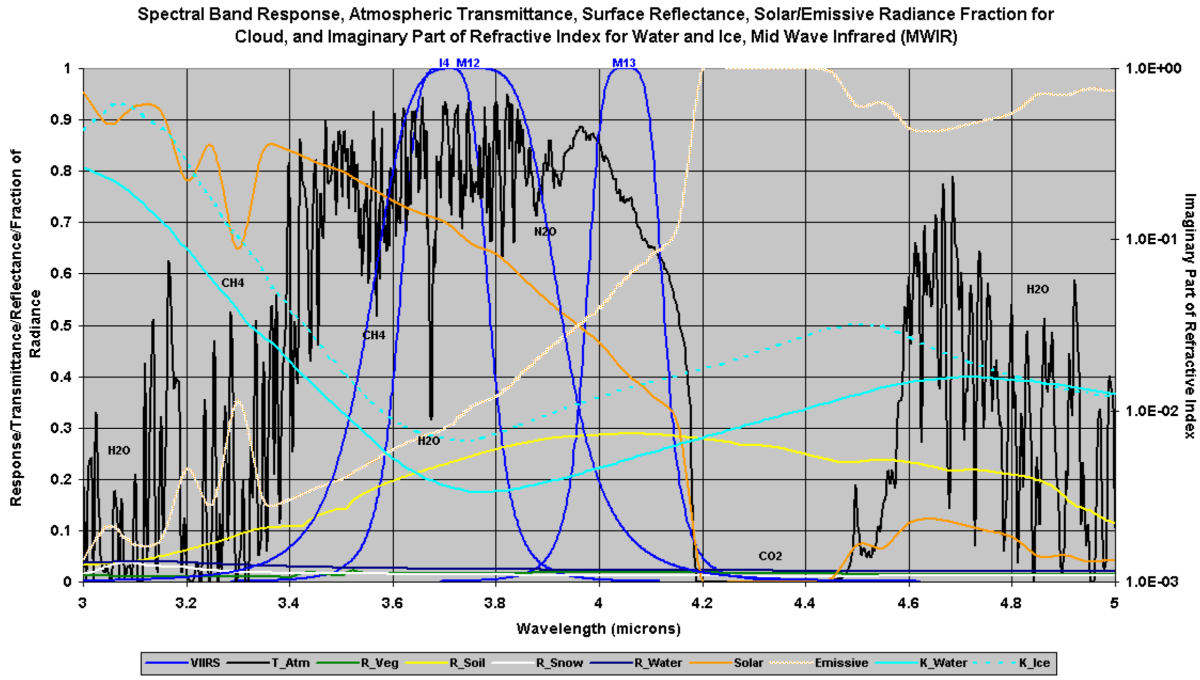


Figure 6. VIIRS spectral bands, medium wave infrared.

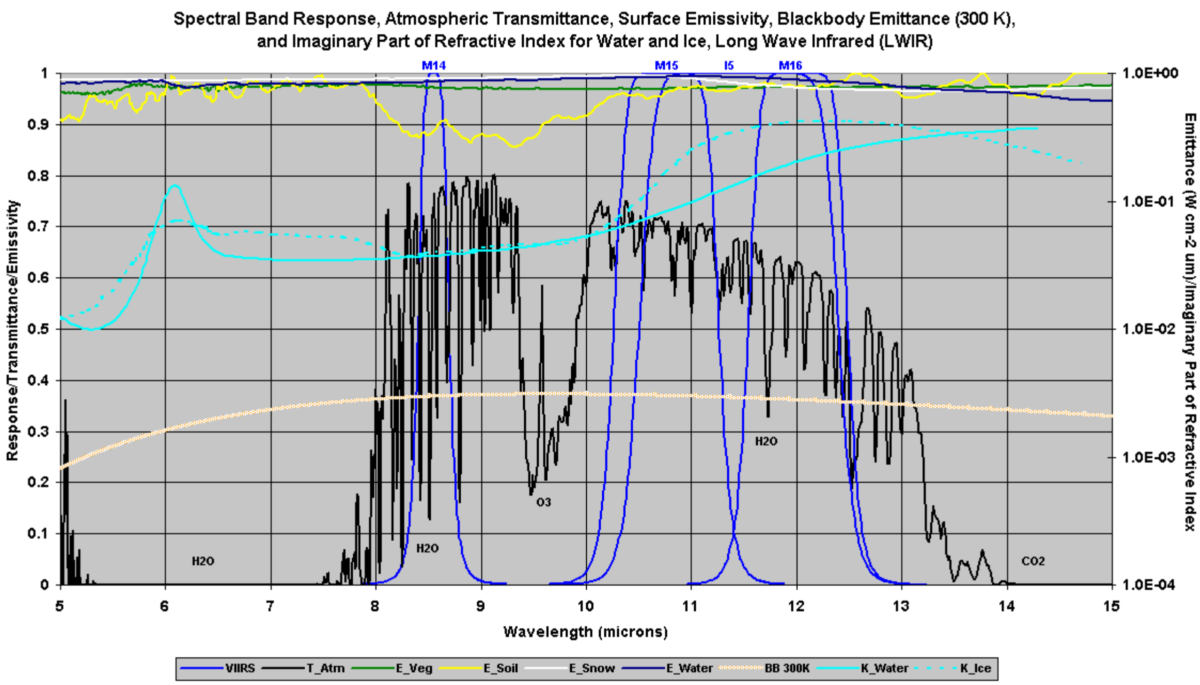


Figure 7. VIIRS spectral bands, long wave infrared.

Table 6 provides the wavelength bands currently being used for VIIRS cloud top parameter retrieval. As described in more detail below, bands centered at 0.672, 3.70, and 10.76 µm are used for IR cirrus and water cloud parameter retrievals, and the band centered at 10.76 µm is used for the Window IR retrieval of cloud top parameters for water droplet clouds. Note that there have been minor changes to band centers during the course of the project. At the time of the writing of this report, the comparable band centers were 0.645, 3.750, and 10.800 µm. Many of the results in this report were produced using those band centers. We do not anticipate significant performance variation for the cloud top parameter retrieval as a result of these changes.

Table 6. Bands Used for Cloud Top Parameter Retrievals. An "x" denotes cloud algorithms that use the band. For algorithms other than cloud top parameters, the band list is not necessarily complete.

VIIRS Band Number	Center λ (µm)	Band Width (µm)	Cloud Top Parameters	Cloud Effective Particle Size*	Cloud Optical Depth*	VIIRS Cloud Mask
M5	0.672	0.02	x	x	x	x
M12	3.700	0.18	x	x	x	x
M15	10.763	1.00	x	x	x	x

2.3 RETRIEVAL STRATEGY

The cloud top parameter retrieval algorithms will use VIIRS radiance data, other VIIRS cloud data (e.g., pixel-level cloud optical depth, effective particle size, and satellite geometry), internal cloud IPs (VIIRS cloud mask and phase), and ancillary data products. The VIIRS cloud mask will identify whether each VIIRS pixel is clear or cloud-contaminated. The phase will provide cloud information, such as ice, water, mixed, or multilayer. The cloud phase information will be used to determine the most appropriate algorithm to retrieve cloud top parameters: the UCLA IR cirrus parameter retrieval algorithm for ice clouds, the UCLA IR water cloud parameter retrieval algorithm for water clouds during night, or the Window Infrared (IR) algorithm for water droplet clouds during daytime or night. These algorithms are described in more detail in Section 3. The UCLA IR retrieval algorithms obtain cloud top temperature, effective particle size, and optical depth for cirrus and water clouds. The Window IR algorithm provides cloud top height for water droplet clouds. Given cloud top temperature or cloud top height, the remaining two cloud top parameters are obtained through the use of an appropriate atmospheric sounding and an interpolation algorithm. At night, CTT will be obtained using both the UCLA and Window IR water cloud algorithms, providing an opportunity for quality control.

3.0 ALGORITHM DESCRIPTION

This section contains seven major subsections addressing the cloud top parameter processing outline; algorithm input and output; the algorithm theoretical basis and mathematical description; algorithm sensitivity to calibration and instrument noise; practical implementation considerations; validation; and algorithm development schedule.

3.1 PROCESSING OUTLINE

3.1.1 General Approach

A high-level flow diagram of the general approach to determining cloud top parameters appears in Figure 8. Input parameters required by the algorithms include pixel-level data from other VIIRS cloud algorithms (optical depth and effective particle size), VIIRS internal products (e.g., cloud mask and phase), VIIRS radiances, and scenario parameters (e.g., sun/sensor geometry and atmospheric scenario). The cloud phase along with day/night flag are used to determine whether retrieval will be made by the Window IR algorithm (water clouds during daytime), the UCLA IR Water Cloud Retrieval Algorithm (water clouds during night) or the UCLA IR Cirrus Parameter Retrieval Algorithm (ice clouds day or night). The Window IR Algorithm returns cloud top height (z_{ct}) and a Cloud Top Parameter Interpolation Algorithm uses z_{ct} together with sounding data to determine cloud top temperature (T_{ct}) and cloud top pressure (p_{ct}). The UCLA IR Cirrus and Water Cloud Parameter Retrieval Algorithms return T_{ct} and the Cloud Top Parameter Interpolation Algorithm uses T_{ct} , together with sounding data, to determine z_{ct} and p_{ct}. Brief descriptions of the UCLA IR Cirrus and Water Cloud Parameter Retrieval Algorithms, the Window IR Algorithm, and the Interpolation Algorithm follow.

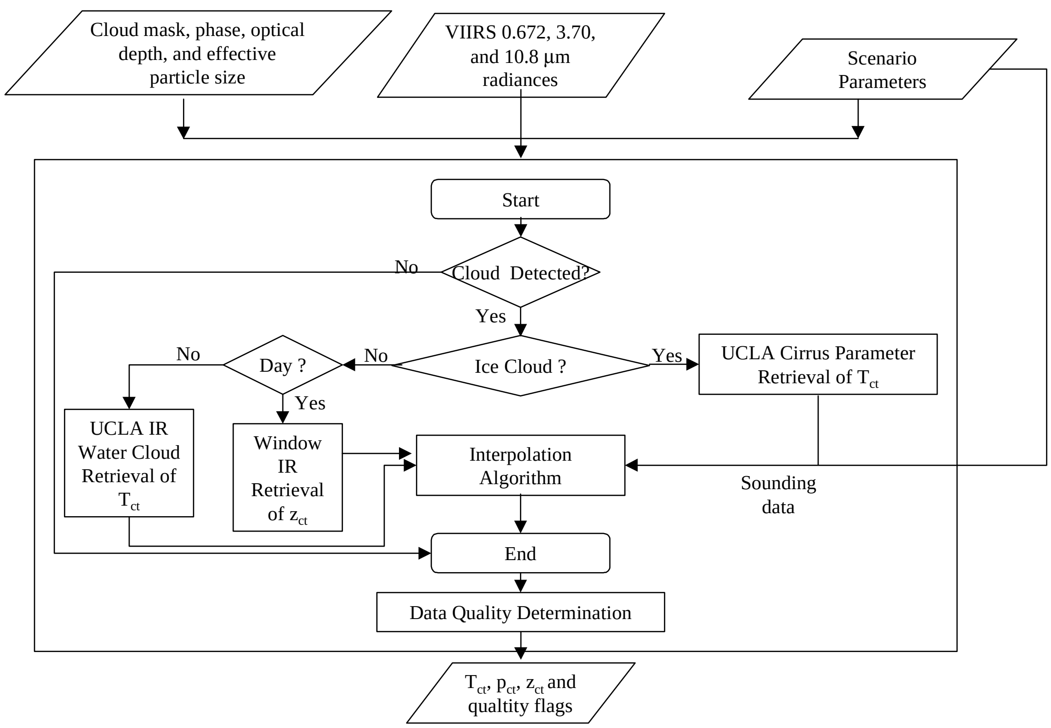


Figure 8. High-level data flow for cloud top parameter retrieval.

3.1.2 UCLA Algorithm for Retrieval of IR Cirrus and Water Cloud Top Temperature

The UCLA IR Cirrus Parameter Retrieval Algorithm calculates cloud top temperature using a 2-band (nighttime) or 3-band (daytime) retrieval algorithm. The algorithm also retrieves cirrus cloud effective particle size and emissivity/optical depth. The cloud top height and pressure are obtained by interpolation using an atmospheric sounding and the Cloud Top Parameter Interpolation Algorithm. The IR Water Cloud Parameter Retrieval Algorithm is similar; thus far, it has been applied to nighttime conditions only.

3.1.3 Window IR Algorithm for Retrieval of Water Droplet Cloud Top Height

The retrieval of cloud top parameters for daytime water clouds is based on the Window IR technique using 10.8 μm radiances. The approach is depicted in Figure 9. To retrieve the cloud top parameters this algorithm requires as input, a measured 10.8 μm radiance value, the VIIRS cloud Effective Particle Size (EPS) Environmental Data Record, the VIIRS Cloud Optical Thickness (COT) EDR, and an atmospheric temperature and moisture profile. Interpolation on a radiance Look-Up Table (LUT) retrieves the cloud top altitude. The pressure and temperature EDRs are then obtained by interpolation using sounding data. Initially, flowdown results were generated by running the Moderate Resolution Atmospheric Radiance and Transmittance Model (MODTRAN) over a range of cloud altitudes, effective particle sizes, and optical depths and scenario conditions. We then transitioned to the UCLA Radiative Transfer Model (Ou *et al.*, 2001). All Error Budget results were produced using that model.

The sensitivity of cloud top parameter retrievals (e.g., CTT, EPS and COT) generally favors the use of algorithms which can compute all three parameters simultaneously (such as the UCLA IR retrieval algorithms) or can use EPS and COT obtained from other algorithms to augment the cloud top parameter retrieval (such as the Window IR algorithm). It should be noted, however, that the Window IR algorithm can provide accurate results even with uncertain knowledge of COT and EPS, when the "effective" optical depth is large. We define effective optical depth as τ(nadir view)/ sin(sensor elevation angle). The sense of the latter parameter is such that 90 deg = overhead and 0 = the horizon. For this reason, the Window IR algorithm is probably appropriate for situtations when EPS and COT are not well-known, but when the effective optical depth is large. This generalizes the use of the Window IR to other scenarios, including thick cirrus clouds. For example, when the pixel-level effective blackbody temperature of a cloud is less than about 240K, the cloud is almost certainly a thick ice cloud. In this case, the single-band Window IR algorithm, rather than the two-band UCLA IR algorithm, may be used to determine CTT. This approach may be preferable, in fact, since the calibration error associated with the 3.7 μm band, which use the two-band approach, increases substantially with decreasing brightness temperature. As the calibration error increases, the retrieval error increases. On the other hand, the calibration error associated with the 10.8 μm band is relatively smaller at cold temperatures. Finally, the use of the Window IR algorithm may also improve results at Edge-of-scan for water clouds during night and ice clouds during both day and night. Even though EPS and COT are less well-known during night, the effective optical depth can be large enough at edge-of-scan to make this uncertainty tolerable in most situations.

So far we have assumed that all VIIRS cloudy pixels are overcast (100% cloud cover within a single VIIRS pixel). For the sub-pixel cloudy case (less than 100% cloud cover), during the post-CDR phase, both the UCLA and Window IR retrieval algorithm will take this into account and analyze algorithm performance at different view angles (nadir and edge-of-scan). The full analysis of sub-pixel cloud effects will be reported in a later version of this ATBD.

The VIIRS 10.8 μm band radiance is subject to water vapor continuum absorption. Using 10.8 μm data directly in the window IR approach without any prior correction will result in under-estimation of cloud top height. Continuum absorption manifests itself in the infrared and millimeter wave window regions of the atmospheric spectrum causing the windows to be less transparent than predicted by molecular absorption alone. For channels intended to be "windows" this is obviously an important factor. This continuum absorption/emission has a smooth frequency dependence making it impossible to ascribe to specific molecular transitions. For most water clouds, cloud altitude usually is lower and there is significant moisture above the cloud top. Precipitable water above cloud top is one of the new NPOESS EDR and can be conveniently used as an additional input to the window IR algorithm to account for water vapor absorption at 10.8 μm very effectively. The scenario parameters required will be detailed in table 7.

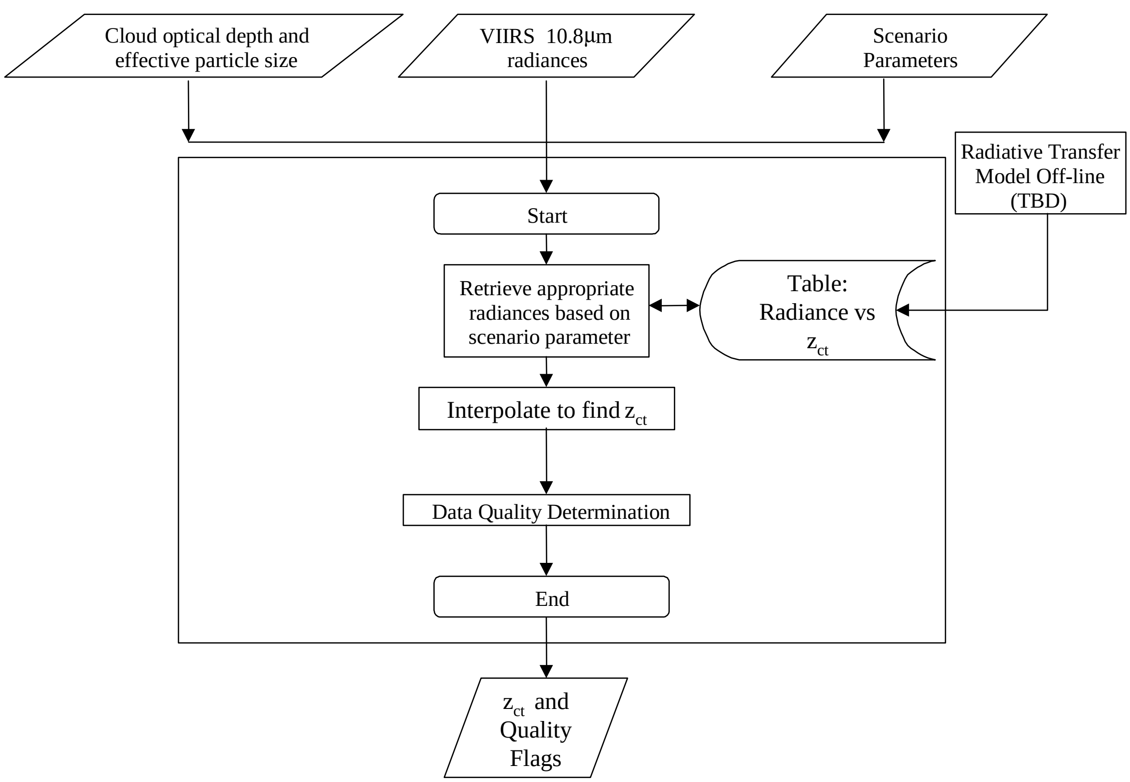


Figure 9. Window IR day time water cloud top height retrieval algorithm.

3.1.4 Cloud Top Parameter Interpolation Algorithm

Given one of the three cloud top parameters (cloud top temperature, height, or pressure) the other two parameters are determined by interpolation using atmospheric sounding data. The hydrostatic approximation is used to interpolate between pressure levels in the sounding; cloud top temperature and height are obtained via linear interpolation between sounding levels. It is assumed that sounding data are always available, either from archived numerical analyses/ forecasts, the Crosstrack Infrared Sounder (CrIS) or the Conical Scanning Microwave Imager/Sounder (CMIS).

3.1.5 Alternative and Complementary Algorithms

A representative alternative algorithm such as the CO_2 slicing method is not applicable to VIIRS since no CO_2 channels are available from the VIIRS instrument itself. However, the coarser resolution (than VIIRS) CrIS sensor has many CO_2 channel measurements that can provide cirrus/water cloud top pressure and emissivity information to complement the UCLA cirrus parameter and window IR water cloud retrievals. For now, we have determined that the UCLA approach, which retrieves cloud optical depth, effective particle size, and cloud top temperature, is capable of meeting SRD threshold requirements. For 25 km HCS, the CrIS sensor will provide multiple pixel cloud top parameters at very high accuracy. A possible synergistic alternative and complementary cloud top parameter retrievals approach will meet not only the threshold requirement, but the objective as well. We recommend researching these alternative and complementary algorithms during the post-CDR phase.

3.2 ALGORITHM INPUT

Table 7 provides VIIRS and non-VIIRS input data required by the Cloud Top Parameter Algorithms.

Table 7. Description of the Input Data Required by the Cloud Top Parameter Retrieval Algorithms

Data Type	Description	Use	Potential Source
VIIRS Radiances	0.670, 3.70, and 10.8 μm radiances	Retrieve cloud top properties	VIIRS
Sensor Viewing Geometry	Sensor zenith and azimuth angles for each pixel	Input to radiative transfer model LUT	Calibrated Radiances SRD
Solar Geometry	Solar zenith and azimuth angles for each pixel	Input to radiative transfer model LUT and algorithm decision tree	Calibrated Radiances SRD
Cloud Mask	Cloud/no cloud for each pixel	Determine if cloud top parameter should be done	VIIRS Cloud Mask algorithm
Cloud Phase	Ice or water cloud flag	Choose cloud top parameter retrieval algorithm	VIIRS Cloud Mask algorithm
Cloud Optical Thickness	Pixel-level optical thickness of water cloud.	Input to radiative transfer model look-up table for Window IR algorithm	VIIRS Cloud Optical Depth algorithm
Cloud Effective Particle Size	Pixel-level effective particle size of water cloud	Input to radiative transfer model look-up table for Window IR algorithm	VIIRS Cloud Effective Particle Size algorithm
Atmospheric Sounding	Atmospheric temperature and relative humidity as functions of pressure and/or height	Input to radiative transfer model look-up table and to infer any two of cloud top height, pressure, and temperature given one of these parameters	NCEP analysis and forecast , CrIS sounding data, CMIS sounding data
Surface Emissivity	In-band emissivity of Earth's surface	Input to radiative transfer model LUT	Emissivity from Spectral Library associated with terrain category database values, e.g., from VIIRS Surface Types-Olson IP
Surface Skin Temperature	Skin temperature associated with pixel region	Input to radiative transfer model LUT	NCEP analysis and forecast, VIIRS Land Surface Temperature EDR and Sea Surface Temperature EDR
Surface Elevation	High resolution ground elevation	Input to cloud top height calculation to define CTH to be above mean sea level	Global high resolution terrain data base

3.3 THEORETICAL DESCRIPTION OF THE CLOUD TOP PARAMETER RETRIEVAL ALGORITHMS

3.3.1 Physics of the Problem

The physics of the UCLA IR Cirrus and Water Cloud Cloud Parameter Retrieval algorithms, which determine effective particle size, optical depth, and cloud top temperature, is described in Ou *et al.* (2001). The discussion here will focus on the Window IR Algorithm, on the determination of cloud top height and pressure given cloud top temperature, and on cloud top pressure and temperature, given cloud top height.

The physical basis of the Window IR Algorithm relies on the following characteristics of the Earth-atmosphere system:

- The radiation reaching the top of the atmosphere in the 10.3 to 11.3 µm region is due primarily to thermal emission by the ground, the atmosphere, and clouds.

- Optically thick clouds, such as most water droplet clouds, are nearly blackbodies in the long-wave IR portion of the electromagnetic spectrum. Most surface materials have emissivities close to one and are nearly blackbodies as well.

- The atmosphere is nearly transparent in the 10.3 to 11.3 µm region, although some attenuation does occur. Atmospheric attenuation is primarily due to absorption by H_2O, CO_2, and aerosols.

- To a reasonable approximation, atmospheric pressure decreases exponentially with height following the hydrostatic equation. Atmospheric temperature decreases monotonically with height in most cases (exceptions being inversions in the lower troposphere and above the tropopause in the stratosphere).

As a result of these characteristics of the Earth-atmosphere system in the 10.3 to 11.3 µm region, the radiation reaching the top of the atmosphere (TOA) is strongly affected by cloud layers, when they are present, permitting retrieval of cloud top parameters. Optically thick water droplet clouds are nearly blackbodies, and most of the upwelling radiation at cloud top is from the cloud itself when a VIIRS pixel is completely covered by cloud. Little radiation from below the cloud layer reaches the cloud top because it is absorbed by the cloud. When optically thick cloud layers are not present, most of the upwelling radiance at the TOA is from the ground. Both the clouds and the ground contribute to the TOA radiance when the clouds are not optically thick; the relative contribution depends on the cloud thickness and effective particle size. The relationship between atmospheric pressure, temperature, and height enables one to determine cloud top pressure and height, if the cloud top temperature is known, or cloud top pressure and temperature, if the cloud top height is known, provided that an atmospheric temperature profile is available.

In describing IR radiative transfer mathematically, we use the plane parallel atmospheric approximation as depicted in Figure 10 for a single layer cloud. In that approximation, it is assumed that variations in atmospheric parameters occur only in the vertical direction. Following Liou (1992), the equation defining monochromatic thermal upwelling intensity at TOA in a plane parallel atmosphere is:

$$I_\lambda(\tau^*) = \varepsilon_\lambda B_\lambda(T_{sfc}) t_\lambda(\tau^*/\mu) + \int_0^{\tau^*} B_\lambda(\tau') t_\lambda(\tau'/\mu) d\tau'/\mu \qquad (1)$$

where:

I_λ = monochromatic radiance

τ = vertical optical depth

τ^* = total vertical optical depth

ε_λ = surface emissivity

λ = monochromatic wavelength

B_λ = Planck function

$B_\lambda(\tau') = B_\lambda(T(\tau'))$

T = atmospheric temperature at specified level

T_{sfc} = skin temperature at Earth's surface

t_λ = monochromatic transmittance = $e^{-(\tau/\mu)}$

μ = cosine of sensor viewing angle

For a cloudy VIIRS pixel which contains energy from both clear and cloudy portions of the scene, we have

$$I_\lambda = (1 - f\varepsilon_{\lambda,c})\, I_{\lambda,clr} + f\varepsilon_{\lambda,c}\, I_{\lambda,cld} \tag{2}$$

where

f = sub-pixel cloud fraction

$\varepsilon_{\lambda,c}$ = cloud emissivity

$I_{\lambda,clr}$ = clear radiance

$I_{\lambda,cld}$ = opaque cloudy radiance

In this report we incorporate the sub-pixel cloud effect (f <1.0) into the cloud optical thickness parameter. For example, COT=1.0 can represent an overcast pixel (a physical COT of 1.0), or a pixel with cloud fraction of 0.5 and physical COT of 2.0. $\varepsilon_{\lambda,c}$ is modeled using UCLA cloud parameterization, to analyze the optical cloud effects on the Window IR cloud height retrieval performance.

Figure 10 provides a notional characterization of the vertical optical depth profile. As depicted here and as frequently occurs in the atmosphere, the largest contribution to optical depth is from the cloud layer. Because the transmission is typically small in Layers 1 and 2 and because the surface emissivity is close to one in most cases, the primary contribution to the radiance at the top of the atmosphere is from the cloud layer and/or the ground. Note also that the Planck emission depends on temperature as well as wavelength, and so the temperature variation with height, including within the cloud, will affect the radiance intensity at the top of the atmosphere.

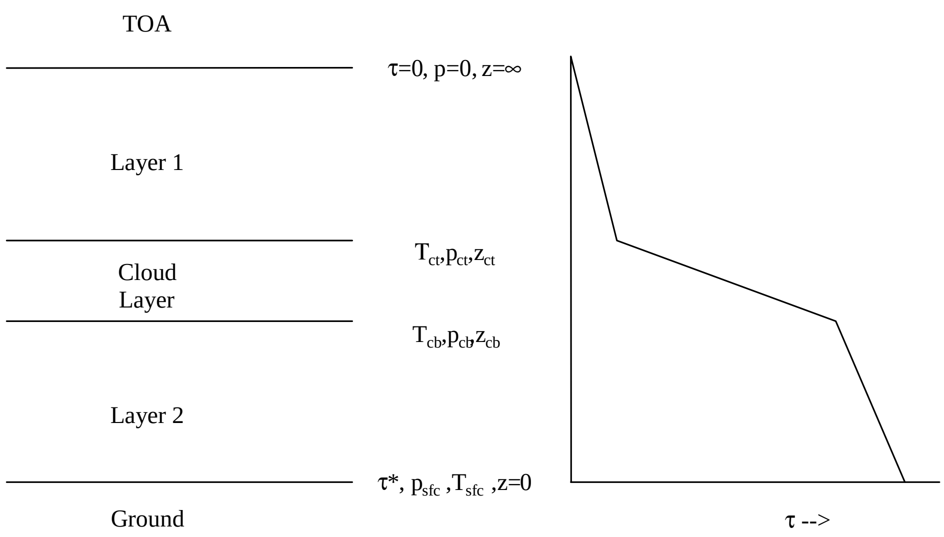


Figure 10. Atmospheric layer construction and notional characterization of the optical depth profile. Symbols are defined in the Definition of Symbols table at the beginning of the document.

The thermal emission model depicted in Equation 1 and 2 is generally a good approximation in the 10.8 µm region. However, there is some scattering in clouds, even at these wavelengths, and a small contribution to radiance can be expected from multiple scattering within the clouds. For this reason, we have included all effects (thermal emission and multiple scattering) in our simulations and our LUT solution We have specified the cloud optical properties, the extinction coefficient, the single scattering albedo, and the asymmetry parameter for water droplet clouds for effective particle sizes ranging from 2 to 32 µm and visible optical depth ranging from 0.05 to 30. These optical property data were obtained from parameterizations of Mie scattering and absorption results developed by Chylek *et al.* (1992). Initially, we used MODTRAN Version 3.7 in the multiple scattering mode using the Discrete Ordinate Radiative Transfer (DISORT) 8-stream. We have since transitioned to the UCLA radiative transfer model (Ou *et al.*, 2001) for all of our work.

3.3.2 Mathematical Description of the Algorithms

A discussion of the Window IR algorithm follows. For a detailed description of the UCLA IR cirrus and water cloud parameter retrieval algorithms, the other algorithms used to retrieve cloud top parameters, see Ou *et al*. (2001)

3.3.2.1 Window IR Algorithm

To support flowdown studies, we have constructed lookup tables for specific environmental scenarios. These lookup tables contain radiance values as a function of cloud top altitude (for altitudes ranging from 1 km to several kilometers), cloud effective particle size ranging from 2 to 32 µm , and cloud vertical optical thickness (visible) ranging from 0.05 to 30. We have assumed a cloud thickness of 1 km. Given pixel-level effective particle size and optical thickness from other cloud EDR algorithms, we determine cloud top height by linear interpolation in the radiance lookup tables, using an "observed" radiance value for which the cloud top height is unknown.

This setup has sufficed for flowdown studies of sensor parameters, but in routine operations the "environmental scenario" will vary from location to location and from day to day, and is defined from the ancillary data sources identified in Section 3.2. There are two approaches to obtaining the radiance lookup tables for the environmental scenario associated with the observed radiance measurements. The radiance lookup tables can either be pre-computed over a range of values of the ancillary data *or* they can be computed on the fly for the environmental scenario corresponding to the horizontal cell for which EDR values will be reported. Either approach requires trade studies and will be performed during the CDR phase. If pre-computed lookup tables are used, they will need to cover the full operational range of the ancillary input data required by the algorithm. The required resolution of the ancillary data will need to be determined. If the second approach is used, an efficient radiative transfer model will need to be identified and the required computational resources carefully studied.

The specified values of cloud optical depth and effective particle size affect the retrieval of cloud top temperature as described in Subsection 3.4. Because the cloud effective particle size and optical depth algorithms also rely on knowledge of cloud top temperature, it is likely that an iterative approach will be necessary. First-guess values of cloud effective particle size and optical depth will be used initially to retrieve cloud top parameters. The retrieved cloud top parameters will then be used by the cloud effective particle size and optical depth algorithms to retrieve those parameters. Next, the retrieved effective particle size and optical depth values will be used in the cloud top parameter algorithm. This process will again be repeated (probably only a few times) until solutions vary little between successive iterations.

In cases where multi-cloud layers occur, the lower cloud layers will also contribute to the TOA radiances. The effect will be less when the upper cloud is optically thick. Nevertheless, some degradation in performance can be expected in the presence of multilayer cloud systems. For example, the MODIS Cloud Top Properties and Cloud Phase Algorithm Theoretical Basis Document (Menzel and Strabala, 1997, page 27) states that "multilayer cloud situations where an opaque cloud underlies a transmissive cloud cause errors in the height of the transmissive cloud of about 100 mb for most cases."

3.3.2.2 Cloud Top Parameter Interpolation Algorithm

This subsection outlines the processes for determining (1) the cloud top temperature and pressure given height and (2) the cloud top pressure and height given temperature for the sounding scenario depicted in Figure 11, where:

T_n = temperature at level n

p_n = pressure at level n

z_n = height at level n

T_{ct} = cloud top temperature

p_{ct} = cloud top pressure

z_{ct} = cloud top height

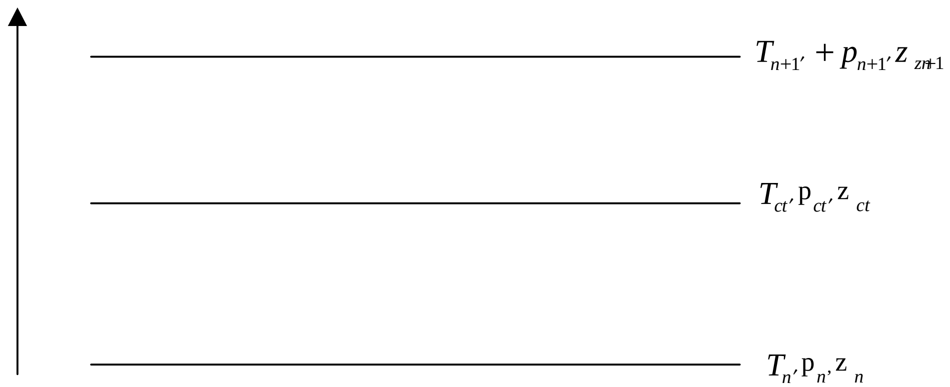


Figure 11. Notation used to define vertical structure.

In the case where z_{ct} is known, then T_{ct} is determined by linear interpolation between T_n and T_{n+1} and p_{ct} is determined via hydrostatic interpolation in the form

$$p_{ct} = p_n \bullet \exp\left(\frac{g(z_n - z_{ct})}{R\overline{T}}\right) \tag{3}$$

where g = .00981 km/s^2, R = gas constant for dry air, and $\overline{T} = (T_n + T_{ct})/2$.

In the case where T_{ct} is known, then z_{ct} is determined by linear interpolation using the temperature profile between z_n and z_{n+1} and p_{ct} is determined as above.

3.3.2.3 Atmospheric Temperature Inversion/Isothermal

The determination of cloud top parameters is more difficult when cloud layers are near atmospheric temperature inversions. In these cases, it is possible that multiple atmospheric layers will have the same temperature, and association of cloud top temperature with a particular atmospheric level may not be possible based only on the radiance measurements. It is possible, however, that the atmospheric structure may provide clues to the probable location of a cloud layer relative to the inversion. The approach to handling inversions should be the subject of future research where high spectral resolution CrIS radiances can provide this inversion or isothermal information.

3.3.3 Archived Algorithm Output

The primary output products of the cloud top parameter algorithms are cloud top temperature, cloud top height, and cloud top pressure. In addition, it is anticipated that a number of data quality flags will be associated with these products. These flags will be implemented in the next version of the software. These flags may address the following:

- Quality of atmospheric sounding (potentially based on the sounding source and associated quality flags).
- Quality of other ancillary input data (e.g, surface temperature, surface emissivity).
- Uncertainty due to the existence of an inversion/isothermal in the temperature profile.
- Quality flags of cloud mask and phase.

- Large difference between UCLA and Window IR water cloud height retrieval.

3.3.4 Variance and Uncertainty Estimates

In this section, the approach used to estimate error budgets for the EDR parameters is described. The total measurement error for a given cloud top parameter can be approximated as follows:

$$E_T^2\,(\mathrm{M}) = \Sigma E_i^2\,(\mathrm{M}) \tag{4}$$

where:

E_T = total error of EDR parameter

M = accuracy or precision metric

E_i = i^{th} component of error contribution

It is assumed that the individual contributions to total measurement error are independent (uncorrelated).

Note also that:

$$E_T^2\,(\text{Uncertainty}) = E_T^2\,(\text{Accuracy}) + E_T^2\,(\text{Precision})$$

The sensor and ancillary input contributions each have several components. Table 8 captures the major contributions to these measurement error sources.

Table 8. Major Contributions to Measurement Error

Error	Error Component	Description
Algorithm	(otherwise referred to as the intrinsic algorithm error)	Retrieval algorithm (model) error assuming perfect sensor and ancillary input data
Sensor	Noise (NEDT)	Sensor noise, assumed to be random, uncorrelated between channels, and uncorrelated spatially
	Modulation Transfer Function (MTF)	Contribution to pixel radiance from outside the pixel.
	Calibration (Absolute Radiometric Accuracy [ARA])	Biases in radiance measurements due to calibration errors; can be due to variations in blackbody emission/reflection sources used for on-board calibration
	Band-to-Band Registration	Relative pointing errors among channels; e.g., channel A looks at a slightly different location than channel B
	Geolocation (mapping)	Uncertainty in knowledge of pixel location
Ancillary Data	Vertical Temperature/Pressure/Moisture profiles	Uncertainty in the knowledge of atmospheric temperature or moisture at one or more levels of the atmosphere. Leads to errors in TOA simulated radiances.
	Surface Emissivity	Uncertainty in the knowledge of surface emissivity. Leads to errors in TOA simulated radiances.
	Surface (skin) Temperature	Uncertainty in the knowledge of surface (skin) temperature. Leads to errors in TOA simulated radiances.
	Effective Particle Size	Uncertainty in the knowledge of effective particle size. Affects the Window IR algorithm.
	Cloud Optical Thickness	Uncertainty in the knowledge of cloud optical thickness. Affects the Window IR algorithm.
	Cloud Mask	Errors in the cloud mask, especially when pixels are identified as cloud-filled when they are actually clear
	Cloud Phase	The cloud top parameters algorithms will be in error when the cloud phase is incorrect, leading to the use of the wrong branch in the algorithm

In general, we parameterize the contributions to measurement errors as follows:

$$E_i = \delta x/\delta y\ \sigma_y \approx \Delta x/\Delta y\ \sigma_y$$

where:

$x =$ M metric values for baseline (no noise) case and for EDR parameter (cloud top temperature, pressure, or height) perturbation

$\Delta x = |x(M) - x(M)_{\text{no noise}}|$

$y =$ value of error contributor (e.g., skin temperature)

Δy = magnitude of the perturbation of the error contributor ∴

$\sigma_y =$ expected standard deviation (uncertainty) of error contributor "y"

3.3.5 Error Budget

The Error Budgets for Cloud Top Parameters are provided in Raytheon VIIRS Error Budget (Y3249). Details other than those provided in the following few sections can be found in that document. The Error Budgets for the cloud top parameters EDRs (Cloud Top Height [CTH], Cloud Top Pressure [CTP], and Cloud Top Temperature [CTT]) are divided into three areas consistent with the specification and with the three algorithms used to produce these EDRs. Separate algorithms are addressed for daytime water cloud, daytime and nighttime ice cloud, and nighttime water cloud. This section summarizes the performances of these three EDRs as a group, since the three parameters are highly inter-related. In general, the CTT threshold accuracy requirements are more stressful than the threshold accuracy requirements for CTH and CTP; therefore, the CTH and CTP thresholds are more easily met. Also, the CTH and CTT SRD accuracy requirements are divided into optical depth regimes while the CTP SRD requirements are not. The SRD states performance requirements in two optical depth regimes: $\leq$ 0.1 (TBR) and > 0.1 (TBR). We have chosen to express the optical depth breakpoint at 1.0 instead, based on performance predictions with full Error Budgets.

3.3.5.1 Daytime Water Clouds

Under daytime conditions, CTH is estimated with the Window IR algorithm using the 10.8 μm channel. The algorithm also uses pixel-level estimates of EPS and COT from the daytime optical property algorithms. The remaining two cloud top parameters are determined using atmospheric vertical profile information. CTH, CTP, and CTT accuracy results are shown in document Y3249. In general, these results show better than objective performance for optical depths exceeding 5 and performance between threshold and objective for optical depth in the 1-5 range for all viewing geometries. For the 0.5 – 1 optical depth range, CTH is better than threshold for all viewing geometries and CTP and CTH are better than threshold for the off-nadir and edge-of-scan geometries. CTP and CTH are greater than threshold for nadir conditions in the 0.5 to 1 optical depth range. As for CTH and CTP precision are better than objective for all optical depth bins and viewing geometries. CTT is better than objective in most cases; exceptions are for nadir viewing geometry within the 0.5 – 1 and 1 – 5 optical depth bins, where performance is between threshold and objective.

The results for the fine resolution products are generally above the SRD threshold for all three parameters. Note that the uncertainty requirements in the SRD for cloud top parameters tend to be more stressful than the corresponding accuracy and precision requirements would suggest, particularly for small optical depths. Furthermore, the CTP SRD uncertainty requirements correspond better with the high cloud (> 7 km) accuracy requirement while the precision requirements correspond bettwer with the low (water) cloud (< 3 km) requirements. For optical depths in the 5 –10 range, which are typical of water clouds, the performances of CTH, CTP and CTT are better than SRD threshold.

3.3.5.2 Daytime/ Nighttime Ice Clouds

Pixel-level CTT is estimated using the UCLA IR Cirrus Algorithm during day and night. The algorithm uses the 0.67 (during daytime), 3.70, and 10.8 μm channels. The remaining two cloud top parameters are determined using atmospheric vertical profile information. For optical depth <

1, nadir and off-nadir performance is better than objective, while edge-of-scan performance exceeds threshold. For optical depths > 1, nadir and off-nadir performances are generally better than threshold and edge-of-scan performance exceeds threshold. Precision performance is generally better than objective for many optical depth bins and view geometries. It exceeds threshold only in the CTH 5 –10 optical depth bin. Fine resolution (nadir) performances for optical depths < 1 are better than threshold for all three parameters. Fine resolution performances for the 1 –5 optical depth bin are again better than threshold for all three parameters.

3.3.5.3 Nighttime Water Clouds

The UCLA IR water cloud retrieval algorithm uses the 3.70, and 10.8 μm bands to determine EPS, COT, and CTT. Error budget analysis shows accuracy results for nadir view and several optical depth bins. These results show that measurement accuracy is better than threshold for optical depth less than 10 and are better than objective for optical depths greater than 10. The budget shows that measurement precision is better than objective for most cases and is between threshold and objective for CTH in the 5 –10 optical depth bin and for CTT in the 1 – 5 and 5 – 10 optical depth bins. Fine resolution product performance for optical depth less than 1 is better than threshold for CTT, at threshold for CTH, and exceeds threshold for CTP. Note that the SRD threshold uncertainty requirements for all of these parameters are TBR and that, in general, these requirements are more stressful than would be obtained by computing the RSS of the corresponding measurement accuracy and precision requirements. In particular, the CTP threshold uncertainty requirement is 50 mb (TBR), while the threshold accuracy requirement for low clouds is 100 mb. The performance of the nighttime water cloud algorithm is impressive. It is anticipated that off-nadir performance should be similar and edge-of-scan performance somewhat degraded relative to nadir. The Cloud Team feels, however, that the Window IR algorithm can compliment this algorithm in scenarios where the effective optical depth is large (e.g., at edge-of-scan). Therefore, overall performance at night is expected to meet threshold requirements.

3.4 ALGORITHM SENSITIVITY STUDIES

Algorithm sensitivity studies were conducted in earlier stages of the project to determine the impact of individual sensor error contributions on algorithm performnace. A number of standard scenes were used to support these studies. These studies led to the initial estimates of sensor performance required to meet or exceed SRD requirements.

The studies were divided into three categories: calibration, instrument noise, and ancillary data errors. Examples of each follow.

3.4.1 Calibration Errors

Calibration errors refer to errors in EDR parameter retrievals due to uncompensated biases in radiance measurements. These particular studies address biases that would cause all thermal, and separately, all solar channels to be biased in the same direction. That is, IR and solar biases are independent. These types of biases occur when the emissivity of the on-board blackbody or the reflectivity of the on-board solar diffuser drifts over time. In these studies, the impact of biases on long-term stability and absolute radiometric accuracy are examined. To examine absolute radiometric accuracy, we use the measurement accuracy metric defined in the SRD:

$$\beta = \left| \mu(\gamma\%) - x_{\mathrm{T}} \right| \quad (5)$$

where

$\mu(\gamma\%)$ is the average parameter retrieval for the same truth value with a γ% radiance perturbation

where

$$\mu = \sum_{\mathrm{N}} x_i \,/\, \mathrm{N} \quad (6)$$

x_{T} is the truth value of the parameter

N is the number of values included in the average.

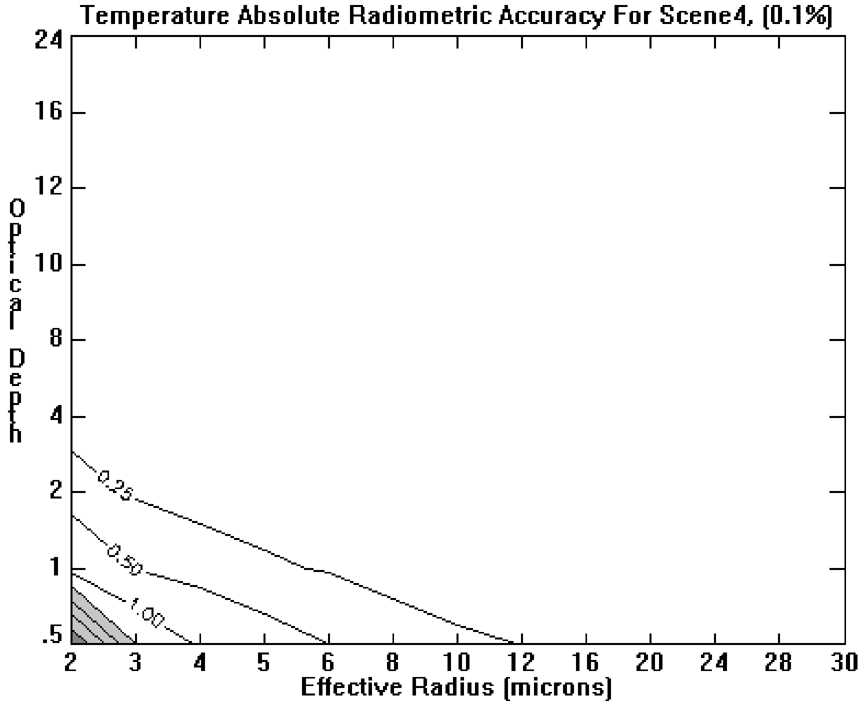
To examine long-term stability, we define a metric similar to the long-term stability metric defined in the SRD. [*Note*: the SRD definition of long-term stability treats time series data. The approximate formula that follows treats perturbations as though they were short-term biases in radiance measurements.]

$$\rho = \sum_{N} \left| \left(x_i(\gamma\%) - x_i(-\gamma\%) \right) \right| / N \quad (7)$$

3.4.1.1 Radiometric Accuracy Results

Figures 12a and b show the results for Scenario 4: a US Standard Atmosphere case, nadir satellite view, and with a water cloud inserted between 3 and 4 km. These results demonstrate the effect on retrieved cloud top temperature of biases of 0.1, 0.5, 1 and 2 percent in the 10.8 μm radiance, for a range of cloud effective particle sizes and optical depths. The light grey shading indicates where errors exceed the Measurement Accuracy objective values and the dark grey shading shows where errors exceed the threshold values contained in the SRD for clouds of optical depth greater than 0.1 (TBR). The size of the bias that can be tolerated tends to increase with effective particle size and optical depth; this is typical of the results for other scenarios. For $r_e = 5$ (a typical size for an altocumulus cloud) and $\tau = 1$, we see that the threshold is met at a perturbation of 1 percent and for optical depths greater than 2, perturbations exceeding 2 percent meet threshold.

It is interesting to examine results for typical effective particle sizes for water droplet clouds, which generally occur in the range 4.0 to 5.0 μm (see Liou, 1992, p. 187). Table 9 shows the bias above which threshold measurement accuracy is exceeded, for $r_e = 5$ and for $\tau = 1$ and 10 for cloud top height, temperature, and pressure. Biases range from about 1 to 5 percent, in general.



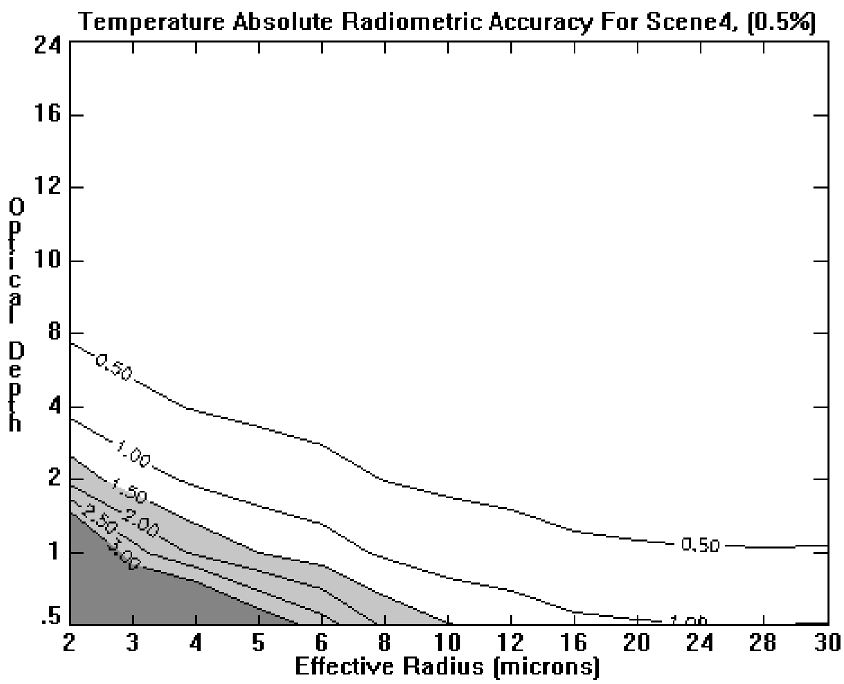
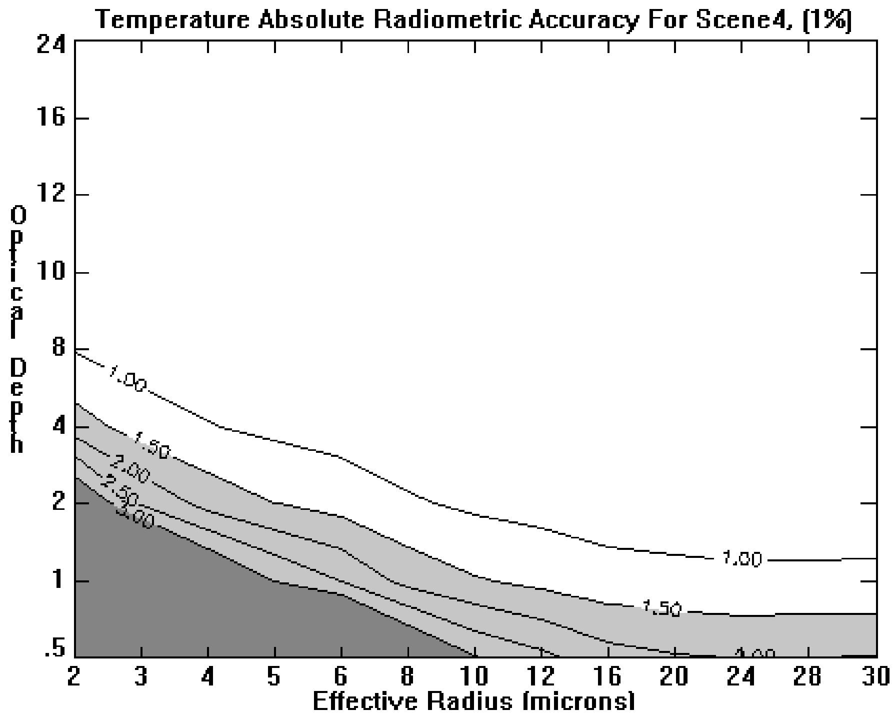


Figure 12a. Radiometric Accuracy results for 0.1% (top) and 0.5% (bottom) perturbations in the 10.8 μm radiances using Scenario 4 and the Window IR algorithm. The measurement accuracy metric is plotted.



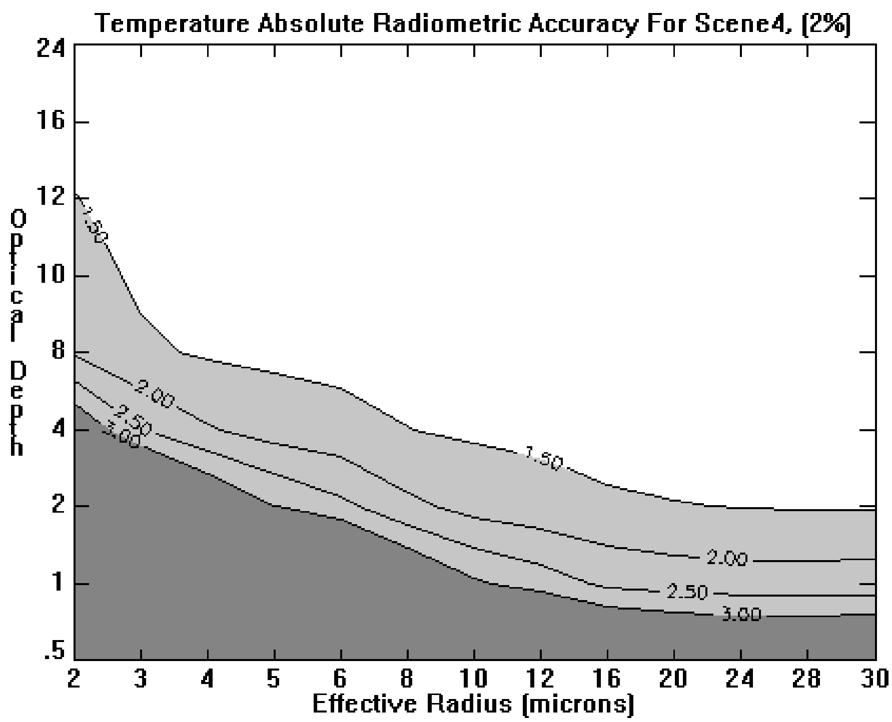


Figure 12b. Radiometric Accuracy results for 1% (top) and 2% (bottom) perturbations in the 10.8 μm radiances using Scenario 4 and the Window IR algorithm. The measurement accuracy metric is plotted.

Table 9. Bias values (in percent) above which threshold measurement accuracy is exceeded for water droplet clouds, with $r_e = 5$ and for $\tau = 1$ and 10.

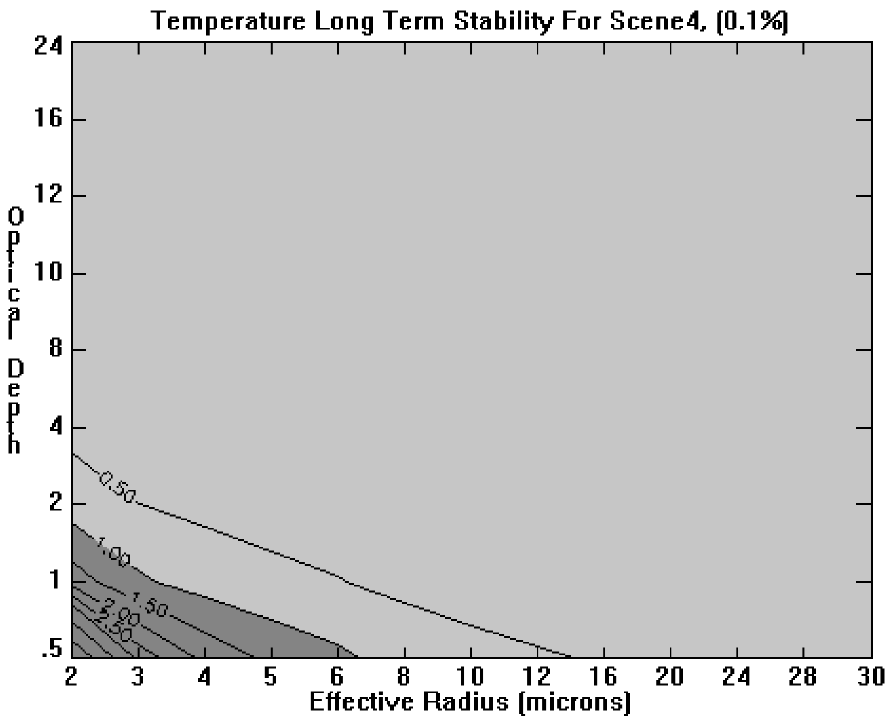
EDR Parameter: Cloud Top Height, Temperature, and Pressure
Sensor Parameter: Radiometric Accuracy
Algorithm: Window IR
Effective Radius: Effective Radius = 5 µm

		Height		Temperature		Pressure	
Scene	**Scene Description**	$\tau = 10$	$\tau = 1$	$\tau = 10$	$\tau = 1$	$\tau = 10$	$\tau = 1$
4	Water Cloud (4/1km), US Standard Veg., θ= 0, θ_0 = Night	5%	5%	1%	4%	1.5%	5%
7	Water Cloud (4/1km), US Standard Veg., θ= 40, θ_0 = Night	5%	5%	1.1%	4%	2%	5%
8	Water Cloud (7/1km), Tropical Veg., θ= 0, θ_0 = Night	5%	5%	0.4%	2.5%	5%	5%
17	Water Cloud (4/1km), US Standard Veg., θ= 55, θ_0 = Night	5%	5%	2%	4%	5%	5%
18	Water Cloud (7/1km), Tropical Veg., θ= 40, θ_0 = Night	5%	5%	0.75%	4%	5%	5%
19	Water Cloud (7/1km), Tropical Veg., θ= 55, θ_0 = Night	5%	5%	2%	4.5%	5 %	5%

3.4.1.2 Radiometric Stability Results

Figure 13 provides results of the computation of the long-term stability metric, as a function of optical depth and effective particle size for scenario 4. The size of the bias that can be tolerated tends to increase with effective particle size and optical depth; this is typical of the results for other scenarios. Biases between 0.1 and 0.5 percent will meet threshold requirements for most optical depths and effective particle sizes. For $r_e = 5$ (typical altocumulus cloud) biases exceeding 0.5 percent can be tolerated for optical depths exceeding 4.

It is interesting to examine results for typical effective particle sizes for water droplet clouds which generally occur in the range 4.0 to 5.0 µm (see Liou, 1992, pg. 187). Table 10 shows the bias above which threshold long-term stability is exceeded for $r_e = 5$ and for $\tau = 1$ and 10 for cloud top height, temperature, and pressure. Biases range from about 0.1 to 0.7 percent, in general. The analysis includes mid-latitude and tropical scenarios for nadir and edge-of-scan cases.



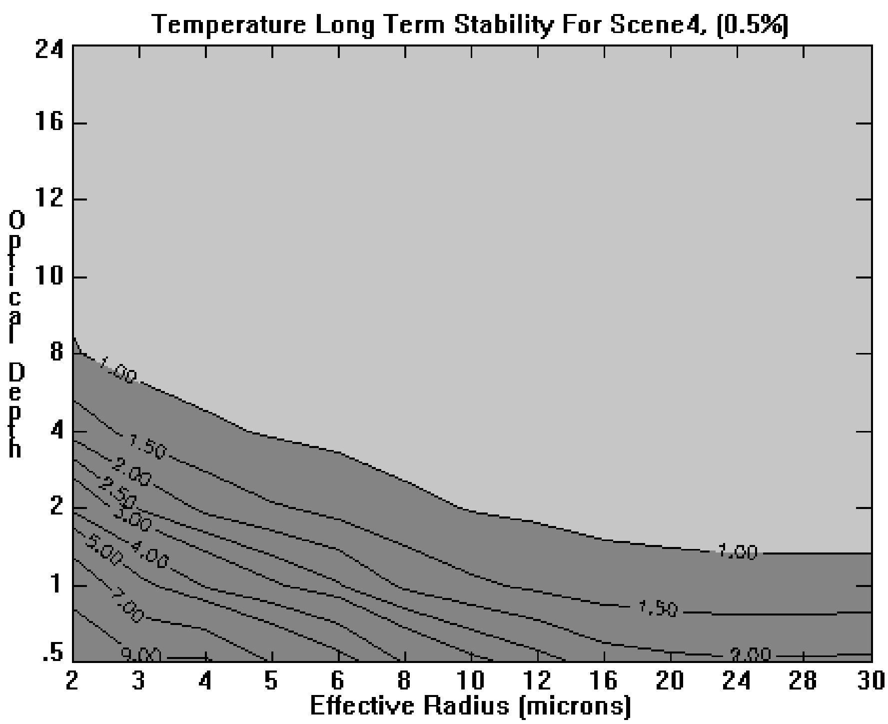


Figure 13. Radiometric Stability results for 0.1% (top) and 0.5% (bottom) perturbations of the 10.8 μm radiances using Scenario 4 and the Window IR algorithm. The long-term stability metric is plotted.

Table 10. Bias values (in percent) above which threshold long-term stability is exceeded for water droplet clouds with $r_e = 5$ and for $\tau = 1$ and 10.

EDR Parameter: Cloud Top Height, Temperature, and Pressure
Sensor Parameter: Radiometric Stability
Algorithm: Window IR
Effective Radius: Effective Radius = 5 µm

		Height		Temperature		Pressure	
Scene	Scene Description	$\tau = 10$	$\tau = 1$	$\tau = 10$	$\tau = 1$	$\tau = 10$	$\tau = 1$
4	Water Cloud (4/1km), US Standard Veg., $\theta = 0$, θ_0 = Night	0.2%	0.7%	0.1%	0.5%	< 0.1%	0.3%
7	Water Cloud (4/1km), US Standard Veg., $\theta = 40$, θ_0 = Night	0.3%	0.75%	0.2%	0.6%	< 0.1%	0.3%
8	Water Cloud (7/1km), Tropical Veg., $\theta = 0$, θ_0 = Night	0.1%	0.6%	< 0.1%	0.3%	< 0.1%	0.3%
17	Water Cloud (4/1km), US Standard Veg., $\theta = 55$, θ_0 = Night	0.4%	0.75%	0.3%	0.7%	0.15%	0.4%
18	Water Cloud (7/1km), Tropical Veg., $\theta = 40$, θ_0 = Night	0.2%	0.7%	0.15%	0.6%	< 0.1%	0.3%
19	Water Cloud (7/1km), Tropical Veg., $\theta = 55$, θ_0 = Night	0.4%	0.7%	0.3%	0.7%	0.15%	0.3%

3.4.2 Instrument Noise

Instrument noise refers to random noise introduced into the measured radiances by the VIIRS instrument. It is assumed that the noise is uncorrelated in time, from pixel-to-pixel, and across bands. Instrument noise was investigated through application of seven noise models provided by SBRS. Noise model 3 is believed to be the best current estimates of instrument specification performance and therefore the detailed EDR performance shown below is using this noise model. The noise is modeled using a Gaussian distribution, with mean and standard deviation dependent on the waveband and magnitude of radiance. The noise models are numbered 1 through 7, with noise increasing with model number.

Two metrics were applied to investigate the effect of instrument noise on EDR retrieval accuracy: measurement accuracy and measurement precision. For these experiments, the measurement accuracy metric was applied as follows:

$$\beta = |\mu - x_T| \tag{8}$$

where symbols are defined as in Section 3.4.1. For these tests, the mean was developed by randomly adding noise 32 times to the unperturbed radiance value(s) used by the retrieval algorithms. The perturbed radiances were then processed through the retrieval algorithm and the measurement accuracy metric computed. This process was repeated for each noise model.

The measurement precision metric is the standard deviation of the retrieved values, relative to the mean of the retrieval values, with the same truth-value for all retrievals.

$$\sigma = \sqrt{\sum_N (x_i - \mu)^2 / (N-1)} \tag{9}$$

If we assume that the response of the EDR retrieval algorithm is linear for small radiance perturbations, we can see that the measurement accuracy metric should be insensitive to noise and that the precision metric should be sensitive to noise. This was found to be the case for all but the largest noise models (i.e., noise models 6 and 7).

Figures 14 and 15 show contour plot of measurement accuracy and precision results, respectively, for a range of optical depths and effective particle sizes for baseline noise model 3. The results are for Scenario 4, which is a U.S. Standard Atmosphere case, nadir satellite view, with a water cloud inserted between 3 and 4 km in altitude. In these plots, the light gray shaded regions are regions where the objective is exceeded and the dark gray shaded regions are regions where the threshold is exceeded. It is obvious that measurement accuracy meets both threshold and objective. Measurement accuracy results for other scenarios are consistent with these findings; therefore, no further instrument noise measurement accuracy results will be shown. On the other hand, measurement precision is affected by instrument noise. Figure 15 indicates that the threshold measurement precision is met for for virtually all r_e and $\tau > 1$, and the objective is met for for $r_e > 4$ and $\tau > 1$. Only in the small region where $r_e < 4$ and $\tau < 1$ is the threshold measurement precision requirement not met.

Figure 16 shows measurement precision results for Scenario 2, a cirrus case. Again, this case is for the U.S. Standard atmosphere, nadir view, and the cirrus cloud is between 9 and 10 km in altitude. For these plots, the results for all effective particle sizes were aggregated and the precision is depicted as a function of optical depth. Note that the measurement precision meets threshold for most noise models for optical depths greater than about 0.5; the threshold is met for baseline noise model 3 for $\tau > 0.125$.

It is interesting to examine results for typical effective particle sizes for water droplet clouds which generally occur in the range 4.0 to 5.0 µm (see Liou, 1992, pg. 187). Table 11 shows the use of the sensor specification for radiometric sensitivity (model 3) for which threshold measurement precision can be met (with a check mark) or marginally met (question mark) for $r_e = 5$ and for $\tau = 1$ and 10 for cloud top height, temperature, and pressure. In general, the sensor specification for radiometric sensitivity is acceptable for all except scene 8 (tropical water cloud with optical thickness=1) temperature EDR.

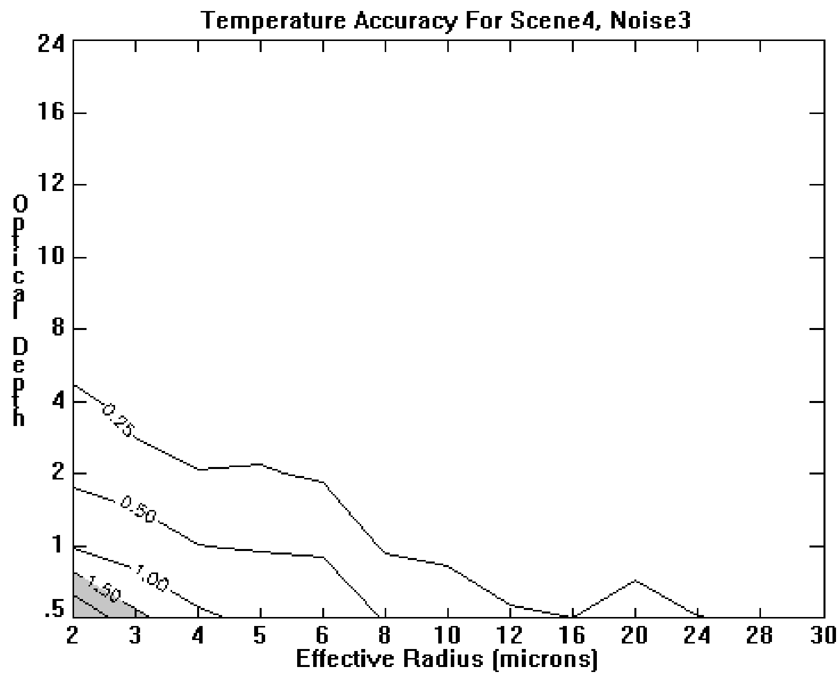


Figure 14. Instrument noise contour plot for measurement accuracy. Scenario 4, Model 3.

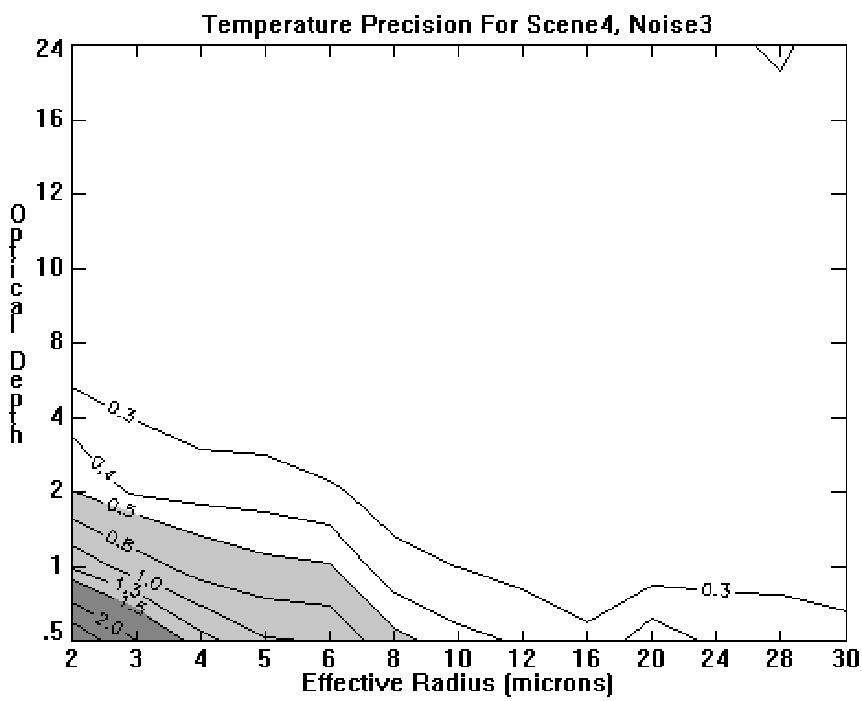


Figure 15. Instrument noise measurement precision. Scenario 4, Model 3.

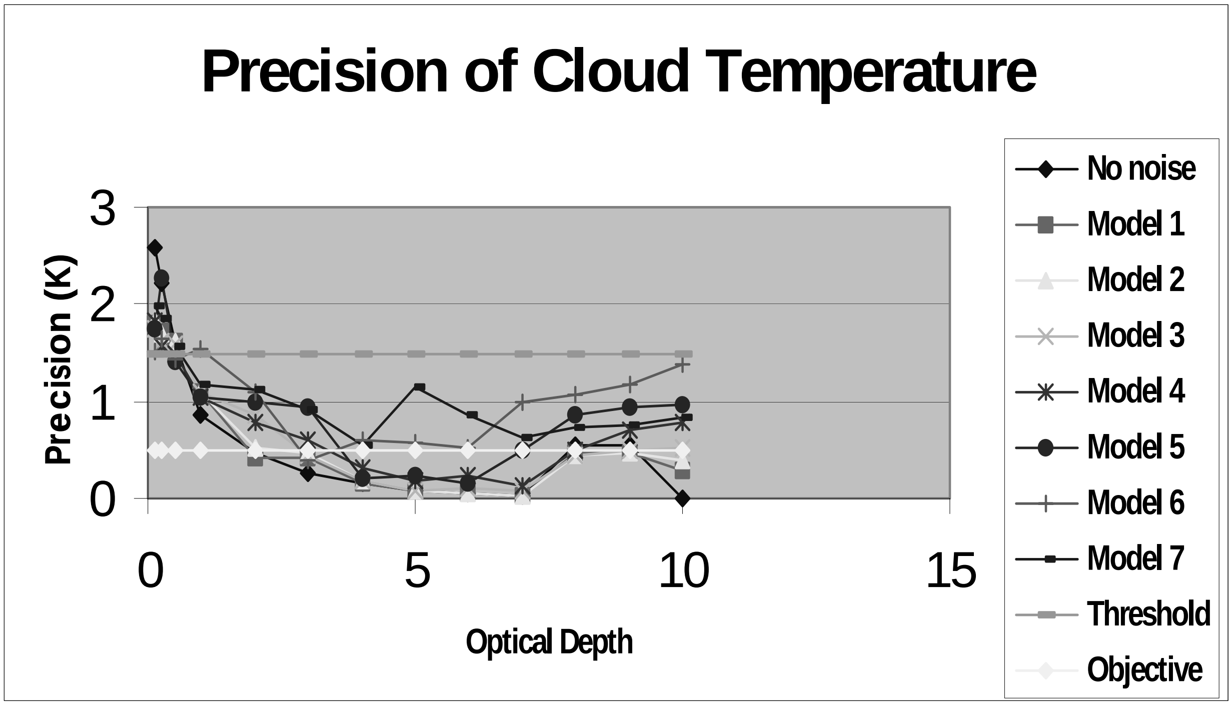


Figure 16. Instrument Noise Measurement Precision Results. Scenario 2.

Table 11. Noise model 3 can met threshold measurement precision for almost all scenes and all cloud top parameters for water droplet clouds with $r_e = 5$ and for $\tau = 1$ and 10. Only for CTT when $\tau = 1$ baseline model is marginally meeting the threshold requirement.

EDR Parameter:	Cloud Top Height, Temperature, and Pressure
Sensor Parameter:	Radiometric Noise
Algorithm:	Window IR
Effective Radius:	Effective Radius = 5 µm

		Height		Temperature		Pressure	
Scene	Scene Description	$\tau = 1$	$\tau = 10$	$\tau = 1$	$\tau = 10$	$\tau = 1$	$\tau = 10$

		Height		Temperature		Pressure	
Scene	Scene Description	τ = 1	τ = 10	τ = 1	τ = 10	τ = 1	τ = 10
4	Water Cloud (4/1km), US Standard Veg., θ = 0, θ_0 = Night	✔	✔	✔	✔	✔	✔
7	Water Cloud (4/1km), US Standard Veg., θ = 40, θ_0 = Night	✔	✔	✔	✔	✔	✔
8	Water Cloud (7/1km), Tropical Veg., θ = 0, θ_0 = Night	✔	✔	?	✔	✔	✔
17	Water Cloud (4/1km), US Standard Veg., θ = 55, θ_0 = Night	✔	✔	✔	✔	✔	✔
18	Water Cloud (7/1km), Tropical Veg., θ = 40, θ_0 = Night	✔	✔	✔	✔	✔	✔
19	Water Cloud (7/1km), Tropical Veg., θ = 55, θ_0 = Night	✔	✔	✔	✔	✔	✔

3.4.3 Ancillary Data

The identification and contribution to performance of uncertainties in ancillary data and other sensor error sources are addressed in the error budget studies in Sections 3.3.4 and 3.3.5.

3.5 PRACTICAL CONSIDERATIONS

The discussions in this section apply mainly to the Window IR and cloud top parameter interpolation algorithms. See Ou *et al*. (2001) for a discussion of the IR Cirrus and Water Cloud Parameter Retrieval Algorithms, which estimate cloud top temperature for cirrus (ice) clouds (day and night) and water clouds at night.

3.5.1 Numerical Computation Considerations

Paragraph SRDV3.2.1.5.4-1 of the VIIRS SRD states the following:

> "The scientific SDR and EDR algorithms delivered by the VIIRS contractor shall be convertible into operational code that is compatible with a 20 minute maximum processing time at either the DoD Centrals or DoD field terminals for the conversion of all pertinent RDRs into all required EDRs for the site or terminal, including those based wholly or in part on data from other sensor suites."

RDR here stands for Raw Data Record. This essentially means that any and all EDRs must be completely processed from VIIRS raw data, including calibration and geo-referencing within 20 minutes from the time the raw data are available. This requirement is a strong reminder that VIIRS is an operational instrument.

A practical issue to be resolved involves the radiative transfer analysis that must be performed to support the Window IR solution. The approach requires up to N radiative transfer solutions for the Specified Environmental Scenario and for a cloud layer positioned in one-kilometer steps from the ground to N kilometers in altitude. The retrieved cloud top altitude is the one for which the solution and VIIRS 10.8 μm radiance measurement best match. A comprehensive radiance LUT is required to apply the algorithm operationally. In the LUT approach, radiance tables are pre-computed and accessed each time a retrieval is performed. During the VIIRS algorithm development CDR phase optimal methods to identify the appropriate LUT will be pursued. The tables must encompass the complete operational range of Environmental Scenarios at sufficient resolution in parameter space to meet retrieval accuracy requirements. As an alternative, on-line radiance calculation will be tested to see if it can meet the processing timeliness requirement for EDR generation.

3.5.2 Programming and Procedural Considerations

3.5.2.1 Programming Considerations

The Window IR and interpolation algorithms are written in the C programming language and should be easily transferrable to other computation environments.

3.5.2.2 Procedural Considerations

Table 12 provides an outline of the procedure for determining cloud top parameters.

Table 12. Cloud Top Parameter Retrieval Procedure

Step	Description
1	Obtain VIIRS data: radiances, sun-sensor geometry, and cloud mask and cloud phase (ice or water cloud) results.
2	Obtain ancillary data required by algorithms.
3A	Ice cloud. Execute UCLA IR cirrus parameter retrieval algorithm. See Ou *et al.* (2001). Go to step 4A.
3B	Water cloud Daytime. Initialize τ and r_e. Execute Window IR algorithm. Go to step 4B.
3C	Water cloud Nighttime. Execute UCLA IR water parameter retrieval algorithm. See Ou *et al.* (2001). Go to step 4A.
4A	UCLA Algorithm. Execute Interpolation Algorithm to obtain cloud top height and pressure from cloud top temperature. Go to step 5.
4B	Window IR Algorithm. Execute Interpolation Algorithm to obtain cloud top temperature and pressure from cloud top height.
5	Store “final” values of cloud top parameters and quality flags in database for aggregation to HC and processing by other EDRs.

3.5.3 Configuration of Retrievals

As previously indicated, the retrieval of cloud top parameters will follow execution of the VIIRS Cloud Mask/Phase algorithm, which provides cloud mask and phase for each pixel. For ice clouds, the UCLA IR cirrus parameter retrieval algorithm will be executed to determine cloud top temperature for ice clouds, day or night. This cloud top temperature will be used to determine other cloud top parameters with the use of sounding (temperature versus height and pressure) data. For water clouds during nighttime, the UCLA IR water cloud parameter retrieval algorithm will be executed to determine cloud top temperature for water clouds. For water clouds during daytime, the Window IR algorithm would be executed. Prior to executing the Window IR algorithm, the UCLA solar retrieval algorithm for optical properties for water clouds will be executed to provide effective particle size and optical thickness information needed by the Window IR algorithm. These two algorithms can also be executed iteratively to determine the cloud top temperature and optical properties that are most consistent with the measurements. The resulting cloud height will be used to determine the remaining two cloud top parameters.

3.5.4 Quality Assessment and Diagnostics

The assessment of the quality of retrievals will fall into four categories: Sensor Parameters; Environmental Scenario; Cloud Scenario; and Ancillary Data. Experience gained through simulations, and eventually by validation, will be captured and used to assess the quality of retrievals and provide guidance to the users of these products in the form of data quality flags. A list of parameters or situations that may influence data quality follows.

- *Sensor Parameters.* The qualities of sensor data include:
  - Sensor noise.
  - Radiance calibration.
  - Geolocation.
  - MTF
  - Band-to-Band registration.
- *Environmental Scenario.* Particulars of the environmental scenario that may affect retrieval accuracy include:
  - Values of Environmental Parameters. Sensitivity studies and flowdown indicate that retrieval accuracy is a function of the particular values of some environmental parameters (e.g, surface temperature, surface emissivity, sounding data).
  - Atmospheric inversion/isothermal identified in sounding.
  - Atmospheric water vapor abaorption correction can improve over-estimation of cloud top height (cloud estimated too high)
- *Cloud Scenario.* The qualities or values of other cloud parameters that may affect retrieval accuracy include:
  - Cloud optical depth. Flowdown results show that retrieval accuracy can be a function of optical depth.
  - Cloud effective particle size. Flowdown results show that retrieval accuracy can be a function of effective particle size.
  - Existence of multilayer clouds. Multilayer clouds are difficult to identify and have an impact on radiance measurements. The primary problem is when a thin cloud overlays a lower cloud layer. Therefore, multi-layer clouds will affect retrievals when a single layer

cloud is assumed in the radiative transfer analysis or retrieval algorithm and a multi-layer cloud actually exists within the field-of-view.

- Satellite viewing geometry. Flowdown results show some sensitivity to satellite view geometry.
- Solar position. Solar position influences UCLA IR cirrus parameter retrievals during daytime.
- Non-overcast cloudy pixel. Sub-pixel cloud results in under-estimation of cloud top height.

- *Ancillary Data*
  - In general, the quality of ancillary data affects the quality of retrievals. This has been explored in the Error Budget studies.

3.5.5 Exception Handling

We define "exception handling" as the procedure for handling missing or degraded data or a degraded processing environment.

3.5.5.1 Missing/Degraded Data

Table 13 lists VIIRS and ancillary data, potential primary and secondary sources of these data, and whether these data are essential or nonessential. We define "essential data" to mean data that are absolutely necessary to meet EDR threshold requirements, and "nonessential data" as data that improve retrievals.

3.5.5.2 Degraded Processing Environment

The most resource-intensive task associated with these algorithms involves executing the radiative transfer model. As indicated previously (Sections 3.3.2.1 and 3.5.1), this may be done "on the fly," or pre-computed radiance look-up tables may be consulted. An interesting compromise would be to build the look-up tables as part of the "operational processing." The radiance results for new scenarios would be archived. If the scenario occurs again (within some tolerance), the radiative transfer model would not be rerun; rather, the previously generated look-up table would be used. This scheme would allow interpolation between look-up tables, as is required for any look-up table solution. It is very likely that within a few months of processing (perhaps spread out over the year), a very representative set of look-up tables will have been developed. At the very least, these tables would be the source of calculated radiance data in degraded processing mode; at most they would be the primary source of such information.

Table 13. Data used by retrieval algorithms, whether the data are essential or nonessential, and primary, secondary, and tertiary data sources.

Data Type	Description	Essential/ Nonessential	Potential Source*
VIIRS Radiances	0.672, 3.70, and 10.8 μm radiances	Essential	1: VIIRS 2: None
Sensor Viewing Geometry	Sensor zenith and azimuth angles for each pixel	Essential	1: VIIRS Calibrated TOA SDR 2: Modeled using satellite ephemeris data
Solar Geometry	Solar zenith and azimuth angles for each pixel	Essential during daytime	1: VIIRS Calibrated TOA SDR 2: Modeled using previous satellite ephemeris data
Cloud Mask	Cloud/no cloud for each pixel	Essential	1: VIIRS Cloud Mask algorithm 2: Cloud/no cloud based on simple thresholding
Cloud Phase	Ice cloud or water cloud flag	Essential	1: VIIRS Cloud Mask algorithm 2: CMIS IWC and CLW data
Cloud Optical Depth	Pixel-level optical depth of ice or water cloud	Essential for Window IR during daytime	1: VIIRS Cloud Optical Depth EDR algorithm 2: Default values
Cloud Effective Particle Size	Pixel-level effective particle size of ice or water cloud	Essential for Window IR during daytime	1: VIIRS Cloud Effective Particle Size EDR algorithm 2: Default values
Atmospheric Sounding	Atmospheric temperature and relative humidity as functions of pressure and height	Essential	1: NCEP analysis 2: CMIS sounding data 3: CrIS sounding data
Surface Emissivity	In-band emissivity of Earth's surface	Essential	1: Emissivity from Spectral Library associated with terrain category VIIRS Surface Types- Olson IP 2: Same, but using database other than VIIRS
Surface Skin Temperature	Skin temperature associated with pixel region	Essential	1: NCEP analysis/forecast 2: VIIRS Land Surface Temperature EDR and Sea Surface Temperature EDR
*1 = Primary Potential Source	*2 = Secondary Potential Source	*3 = Tertiary Potential Source	

3.6 ALGORITHM VALIDATION

The Cloud Integrated Product Team (IPT) has or will have access to a number of data sources that could be used to validate the Cloud Top Parameter retrieval algorithms. These sources include the following:

- Radiance data collected by the MODIS Airborne Simulator (MAS), with cloud tops determined from the on-board lidar data.
- MODIS data when available, together with the use of data from associated retrieval algorithm validation campaigns.

The validation effort should be able to take advantage of past and planned cloud field campaigns (such as FIRE-I, FIRE-II, ARM Spring 2000, FIRE Tropical 2002/2003, and the Terra validation studies). Regardless of the data used, it is essential that the data sets include reliable radiance data at or very near the proposed VIIRS wave bands, all required ancillary data, and an accurate description of the associated cloud parameters (type, base, height, optical properties, etc.) for ground truth. During the CDR phase at least one MODIS data set will be used to test cloud top parameter processing performance and provide these analyses in an upated ATBD. The required validation data and procedures that can be used for validating algorithm performance can be briefly summarized as:

- Collect statistically significant samples of co-located in-situ cloud parameter measurements and VIIRS-like measurements.
- Modify/create VIIRS-like measurements with VIIRS instrument specification noise.
- Perform EDR retrieval using ATBD described algorithms.
- Co-register in-situs and EDR retrievals by taking into account spatial, temporal, and viewing discrepancy.
- Perform statistical accuracy, precision, and uncertainty estimates of EDR using retrievals and in-situs.

3.7 ALGORITHM DEVELOPMENT SCHEDULE

Next phase algorithm development will include the following:

3.7.1 UCLA and Window IR water cloud top height retrieval comparison

3.7.2 Non-overcast pixel cloud top parameters retrieval analysis

3.7.3 Implement water vapor absorption correction for 10.8 micron channel before performing Window IR algorithm

3.7.4 Implement multiplelayer cloud retrieval algorithm

3.7.5 Validate UCLA/Window IR cloud top parameter retrieval algorithm using Terra MODIS data

3.7.6 Revise/update ATBD to reflect all phase changes and enhanced algorithm performance

4.0 ASSUMPTIONS AND LIMITATIONS

4.1 ASSUMPTIONS

The major assumptions listed below relate to the Window IR and Cloud Top Parameter Interpolation Algorithms. See Ou *et al*. (2001) for a description of the assumptions made in the UCLA Cloud Parameter Retrieval Algorithm.

- The retrieval algorithm is based on plane-parallel radiative transfer theory. Horizontal inhomogeneities in cloud and environmental parameters and their effects on radiative transfer are not modeled.

- At this time, multilayer cloud conditions are not modeled in the radiative transfer solution. Degraded performance is expected when multilayer clouds are present within the same pixel.

- It is assumed that the atmosphere is in thermodynamic equilibrium and that the hydrostatic approximation applies.

- It is assumed that the optical properties of water droplet clouds are not sensitive to the exact shape of the particle size distribution.

- It is assumed that no sub-pixel clouds exist.

- It is assumed that 10.8 micron channel is not affected by aerosol absorption.

4.2 LIMITATIONS

No major limitations have yet been identified for the Window IR and cloud top parameter Interpolation Algorithms. The algorithms are applicable both day and night, and results indicate accurate retrievals are possible over the full range of viewing geometries. See Ou, *et al.* (2001) for a description of the limitations of the UCLA Cloud Parameter Retrieval Algorithm. We do expect degraded performance when multilayer and sub-pixel clouds are present within pixels and when a temperature inversion/isothermal is present in the atmosphere. The impacts of these conditions on retrieval accuracy have not yet been quantified.

5.0 REFERENCES

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